Accessing sustainable hydrogen energy technologies: Strategies for remote Antarctic communities

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Accessing sustainable hydrogen energy technologies: Strategies for remote Antarctic communities

by

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David Pointing

Abstract

This research project addresses current limitations in the area of energy technology integration by improving understanding of the interactions between novel energy technologies and energy-using communities. The study focuses on the interface between systems using renewable and hydrogen energy technologies and the communities of scientists working in the remote, harsh and pristine Antarctic environment. The project is multi-disciplinary and includes technical analysis of specific energy technologies and investigation of the social issues that influence the interaction of energy users with such technologies. The primary research objective is the development of tailored strategies and recommendations to help the Australian Antarctic research community access appropriate and sustainable energy solutions.

Elements of the research include: [1] Review of global energy issues and the emergence of novel solutions such as renewable and hydrogen energy technologies. [2] Overview of the international Antarctic research community and energy-related issues, with specific review of Australia's operations. [3] Technical analysis of potential roles of hydrogen technologies. [4] Application of computer modelling tools (HYDROGEMS) to simulate the operation of a wind-hydrogen system at an Antarctic station. [5] Engagement with related communities to identify issues that influence the community's interaction with innovative energy solutions. [6] Evaluation of the potential to apply experiences relating to sustainable energy use in Antarctic operations to other energy-using communities.

The major conclusions and recommendations from the research include: [1] hydrogen energy technologies are technically viable now for use in Antarctic operations [2] even though there are limitations in hydrogen energy technologies and the design and evaluation tools that are currently available; [3] Social issues are the biggest barrier to the implementation of novel energy technologies such as hydrogen into the Australian Antarctic community; [4] Local environmental issues are not significant as drivers for change to Antarctic energy systems; [5] The use of hydrogen energy technologies in small-scale applications is expected to be the largest and most viable market for hydrogen technologies in Antarctic applications in the near-term; [6] efforts to introduce renewable energy generation and storage systems should focus on achieving less than 100% independence from fossil fuel supplies; [7] Antarctic communities are more likely to benefit from the activities of others in the evaluation and implementation of hydrogen energy technologies than to be leaders in the development of early markets, even though certain characteristics do make them attractive as early adopter markets; [8] The high level of technical and social/cultural changes required within communities to facilitate a transfer away from fossil fuel-based energy economies will require carefully developed strategies.

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Terms and Acronyms

AA	RSV Aurora Australis
AAD	Australian Antarctic Division
AGO	Australian Greenhouse Office
APU	Auxilliary Power Unit
ASPAs	Antarctic Specially Protected Areas
ATCM	Antarctic Treaty Consultative Meeting
ATS	Antarctic Treaty System
ATV	All Terrain Vehicles
AusAID	Australian Agency for International Development
BCSE	Business Council for Sustainable Energy (Australian)
BIPV	Building Integrated Photovoltaic
BMCS	Building Management and Control System
CEP	Committee for Environmental Protection
CHP	Combined Heat and Power system
CNG	Compressed Natural Gas
CO2	Carbon dioxide
CoE	Cost of Energy
COMNAP	Council of Managers of National Antarctic Programs
DEG	Diesel Electric Generator
DEH	Department of Environment and Heritage (Australian Government)
DSM	Demand-side management
EIL	Electrolyser Idling Load
EMA	Early Market Adopter
EPH	Emergency Power House
EU	European Union
FC	Fuel cell
GNI/pop	Gross National Income per capita
H2	Hydrogen
HART	Hydrogen and Allied Renewable Energy Technologies
HEGS	Hydrogen Electric Generator System
HSAPS	Hydrogen Stand Alone Power System
I&D	Innovation and Development Engineer
IASOS	Institute of Antarctic and Southern Ocean Studies
ICE	Internal combusion engine
IEA	International Energy Agency
IFE	Institute for Energy Technology (Norway)
IGY	International Geophysical Year
INE	Icelandic New Energy
IPCC	Intergovernmental Panel on Climate Change
IPHE	International Partnership for the Hydrogen Economy
IPY	International Polar Year
kW	kilowatt
kWh	kilowatt hour
LPG	Liquid Petroleum Gas
MDGs	Millennium Development Goals
MH	Metal hydride
Mpa	Mega pascal

NEM	National Electricity Market
NordSESIL.net	Nordic Network for Sustainable Energy Systems in Isolated Locations
OECD	Organisation for Economic Cooperation and Development
PEM	Proton Exchange Membrane (fuel cell)
PURE	Promoting Unst Renewable Energy
PV	Photovoltaic
R&D	Research and development
RAPS	Remote Area Power System
RE	Renewable energy
RSV	Research and Supply Vessel
SAB	Special Antarctic Blend (diesel fuel)
SAPS	Stand Alone Power System
SCALOP	Standing Committee on Antarctic Logistics and Operations
SCAR	Scientific Committee on Antarctic Research
TW	Terra watt
UN	United Nations
UN FCCC	United Nations Framework Convention on Climate Change
UN WCED	United Nations World Commission on Economic Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
URC	UNEP Risø Centre for Energy, Climate & Sustainable Development
US	United States
UTS	University of Technology Sydney
VAC	Volts Alternating Current
VDC	Volts Direct Current
W	Watt
WBG	World Bank Group
WEA	World Energy Assessment
WHEC	World Hydrogen Energy Congress

Chapter 1. Introduction

Antarctica is a land of extremes – the coldest, driest, windiest, highest, harshest, most remote and most pristine continent on Earth. In spite of these conditions, or often because of them, people live and work in the Antarctic region. Many are scientists, examining important issues such as global climate change indicators, and working for government programs at research bases established on the continent. Modern energy services are essential for the operation of these bases to support technology-dependant science programs but also to keep people warm and productive in the freezing polar conditions. The operating principles and the components of their energy systems are comparable to those used in communities of all sizes around the world – they are based on the consumption of fossil fuels. As concern grows around the world about the sustainability of all anthropogenic energy systems and the influence on issues such as global climate change, consideration logically falls on the energy systems used in Antarctica.

This thesis provides a multi-disciplinary and practical analysis of Antarctic energy systems and the potential to develop and implement viable and more sustainable energy supply solutions for Antarctic communities. It also investigates the energy technology-based relationships that may exist between communities in Antarctica and other regions of the world.

The Australian Government's Antarctic research program, which is a focus for much of the work in this thesis, provides clear examples of the circumstances faced by communities in Antarctica in operating energy systems, as well as the need for and challenges associated with developing more sustainable solutions. The program operates through the Australian Antarctic Division (AAD), including maintaining three permanent scientific stations on the Antarctic coast. Energy services for these stations, providing electricity, heat, water production, waste disposal and transportation, are met with liquid fossil fuels (a diesel derivative). This requires the import of millions of litres of fossil fuels each year to the stations. These fuel supplies are taken by ship from Australia, transported across the rough Southern Ocean, and stored and consumed in the pristine and sensitive polar environment.

A range of factors, including the growing purchase price of fossil fuels, the high embodied cost of delivering the fuels to Antarctica, and the local and global environmental impacts of using fossil fuels, are prompting the consideration and development of more sustainable energy systems within Antarctic communities.

Australia is a leader within the international Antarctic research community in terms of pursuing more sustainable energy systems. Their preliminary efforts to date have focused on improving the efficiency of generation and use of energy from conventional fossil fuel-based energy systems. After a period of analysis, they have also begun using renewable energy resources (wind) on a substantial scale at one of their stations (Mawson). The increased use of renewable energy and associated reductions in fossil fuel usage is constrained by their inability to adequately store the intermittent renewable energy resources or to meet transport energy requirements. A number of options have been considered, including the use of hydrogen as an energy storage mechanism.

1.1 Background to the research

Discussions initiated by the author in 2001 with the Australian Antarctic community about research into the strategic issues associated with the sustainability of Antarctic energy systems confirmed that identifying methods of storing renewable energy resources that were suitable for use in Antarctica was a valid and valuable area of interest. The discussions prompted a basic and broad request for assistance from the community on the viability, suitability and practical details of hydrogen energy technologies and methods of accessing the relevant technologies.

A six-month research project was subsequently undertaken by the author in 2001 which confirmed the theoretical and broad viability of hydrogen technologies for use with renewable energy resources in Antarctic operations [1]. The research made several major conclusions:

1. Hydrogen technologies were not yet commercially available or viable, but their development was showing great momentum and early-market products should be expected in the near future (5 years),
2. Hydrogen technologies appeared to be compatible with the energy needs and usage patterns of Antarctic operations, but would need to be evaluated in much greater detail if technologies were to be selected for specific applications.
3. Many cultural and social issues were linked to the evaluation and introduction of energy technologies, particularly novel technologies. These issues had far more potential to negatively influence the use of hydrogen technologies than any limitations within with the technologies. A much greater understanding of the interface between the Antarctic community and their energy technologies would be needed if changes were to be made to the energy systems.
4. This understanding of the use of hydrogen technologies and the people-technology interface could be undertaken in parallel with the continued development of commercially-mature hydrogen technologies by external parties so that the Antarctic community could be ready to use the technologies when they are available.
5. The high energy costs of Antarctic operations and the pristine nature of the operating environment provide strong motivations for the introduction of energy supply technologies that offer independence from fossil fuels and less environmental impact. These factors could motivate Antarctic operators to purchase energy technologies that are too expensive for consumers in conventional markets.

Further evaluation of the preliminary study identified a need to further investigate the relevance of hydrogen technologies to Antarctic communities and the issues surrounding their possible introduction into the communities if more sustainable energy solutions based on hydrogen energy were to be effectively evaluated. Such an investigation would need to consider the use of hydrogen technologies in Antarctic operations from a number of perspectives. The investigation would need to include: a conventional engineering-style evaluation of the technologies and energy demands, practical information about next steps forward for the community if suitable technologies were identified through the engineering analysis, and close consideration of the interface of the Antarctic community and the relevant technologies. Outcomes from the community-technology interface research should be integrated with the other elements of the analysis.

Analysis of the preliminary study also indicated that there is an academic opportunity to investigate the relevance of activities in Antarctica, and studies on sustainable energy technologies, to other efforts around the world that relate to novel energy technologies such as hydrogen. Outcomes from a detailed analysis of the potential use of hydrogen technologies in Antarctic operations could be transferable to other selected communities. In addition the economic motivation for Antarctic communities to purchase relatively expensive energy technologies could be relevant to broader efforts to develop markets for hydrogen energy systems.

These two factors were subsequently used to conceive and define a doctoral research project; the need for further work to address the Australian Antarctic community's request for assistance on understanding the use of hydrogen technologies in their operations, and the broader academic role to investigate possible links between Antarctic energy systems and wider energy markets.

1.2 Research goal

This research project aims to address current limitations in the area of effective energy technology integration by improving understanding of the interactions between novel energy technologies and energy-using communities. The study focuses on the interface between systems using renewable and hydrogen energy technologies and the communities of scientists working in the remote, harsh and pristine Antarctic environment. The research project is multi-disciplinary in approach, and covers both components of technical (engineering) analysis of specific energy technologies in defined scenarios and the social issues that influence the interaction of energy users with such technologies. The primary research objective is the development of tailored strategies and recommendations to help the Australian Antarctic research community identify and access appropriate and sustainable energy solutions.

1.3 Research tasks

The following are developed through the research as the prime tasks in this study:

1. To conduct a comprehensive evaluation of the roles that hydrogen energy technologies can play in the Australian Antarctic communities operations, specifically when coupled with renewable energy technologies.
2. To perform a detailed engineering analysis of the technical viability of using hydrogen technologies for large applications in partnership with renewable energy technologies. The analysis should aim to be as 'real world' as possible to provide the AAD with highly relevant information to guide their future ambitions with Mawson station.
3. To engage with the Australian Antarctic community to identify and understand the non-technical issues associated with the evaluation and implementation of hydrogen technologies, and to enable assessment of the appropriateness of hydrogen technologies for the community.

As the research integrates three complex issues, and each issue is assessed to a sufficient level as to make the analysis worthwhile and meaningful as both an independent piece of work and when integrated with the other components in the context of the research goal, the research is a large body of work. The associated thesis is subsequently also large. Upon reflection, the technical issues or the social issues analysis would have provided ample challenge alone to meet the needs of a doctoral research project. However, a core tenet of this research is the need to actually address the issues simultaneously – for too long the engineering elements of energy system evaluation bas been examined in isolation from the social elements.

The approach taken to the research problem also contributes to the size of the thesis – the analysis begins very broadly to encapsulate all possible contemporary energy issues as a foundation for evaluating the use of hydrogen in Antarctic operations and establishing possible linkages between communities in Antarctica and other parts of the world. The initially broad review logically reviews issues to a point where hydrogen technologies and Antarctic communities are the focus of discussions, and specific research tasks can be defined. The three research tasks are separately addressed, examining the technical and non-technical elements of hydrogen energy use in Antarctic operations. The integration of the research outcomes from the different elements is subsequently discussed, leading to final conclusions from the research. There are also comprehensive supporting appendices with additional information relating to the three experimental programs.

1.4 Overview of the research thesis

The thesis begins with a literature review in Chapter 2 that analyses the importance of energy in modern society, examines the characteristics of conventional energy systems and the subsequent need for changes, and identifies a range of actions and strategies that are available to communities to make their energy systems more sustainable. The chapter concludes with an analysis of the potential for a future without dependence on fossil fuels and the need to develop alternative energy 'carriers'. Hydrogen energy technologies are presented as highly regarded solutions.

The future roles of hydrogen energy technologies in the global energy economy are evaluated in Chapter 3. The concept of hydrogen as an 'energy carrier' and the associated processes and technologies are introduced.

To drive the introduction of the technologies into mainstream society for both renewable and hydrogen energy technologies, the development of comprehensive strategies has been recommended. Existing strategies have tended to focus on technical aspects of the challenges faced by the technologies due to the relative immaturity of hydrogen technologies. However, as the technologies have matured in recent years the strategies have begun to integrate non-technical issues as well. A common approach to addressing the barriers faced by hydrogen technologies is to focus on niche applications for the development of early adoption markets. Communities in remote locations are suggested as early markets.

Antarctic communities are obviously located in remote locations and so would appear to fit well with the suggestions to use them as early adopters for hydrogen and renewable energy technologies. Over the course of the research, several demonstration and research projects have applied this strategy and developed wind-hydrogen energy systems for communities in the Arctic and sub-Arctic regions [2, 3].

Chapter 4 subsequently provides a broad overview of the international community of scientists who work in Antarctica and the legal, environmental and operational parameters that apply to their activities. The overview, and associated case study of the Australian Antarctic program, indicates that several possible motivations exist for Antarctic communities to pursue more sustainable energy solutions than the fossil fuels that are predominantly used at present.

Chapter 5 examines in detail the concept of selecting 'appropriate' energy technologies for specific solutions, building on from the review of how and why conventional energy technologies have failed to provide appropriate solutions for a large proportion of the world's poorer populations in Chapter 2. The approach presented outlines how all the key elements in an energy system and their integration must be identified and considered during the design and selection of energy systems to ensure that the energy needs of a user or community are appropriately met. A six-step process is also presented with suggested practical actions for securing the information required for a specific situation and energy using community.

Previous research and practical activities undertaken within the Australian Antarctic community, including prior work by the author, have addressed some of the tasks in the 'six-step process' presented in Chapter 5 for evaluating and identifying appropriate energy technologies [1, 4, 5]. The need is identified to specifically apply this analysis to the use of renewable and hydrogen energy technologies in their operations.

Chapter 6 derives and presents the three specific tasks addressed in the research. It begins with a summary of the main themes from the literature review and draws the necessary conclusions from the material to identify and define the research tasks. The tasks are subsequently addressed in Chapters 7, 8 and 9.

Chapter 7 provides a broad overview of the many and varied types of energy-consuming activities that are undertaken during Antarctic research expeditions, and proposes potential roles for hydrogen energy technologies in delivering energy services in support of these activities.

The chapter also illustrates that the diversity of choice in where hydrogen technologies can be used and the range of related opportunities and potential issues will present challenges to Antarctic communities in identifying when, where and how to implement hydrogen technologies.

Chapter 8 investigates the use of hydrogen energy storage technologies at the permanent Australian Antarctic station 'Mawson' through the application of detailed computer simulations of the station's energy system. The experiments are designed to investigate the conditional use of existing hydrogen energy system tools and models to represent functioning Antarctic stations, and explore the implications of using various energy system designs and components. The simulations utilise 'real world' data provided by the Australian Antarctic Division, and enable a concluding recommendation for the integration of hydrogen technologies into the existing wind-diesel system that is technically feasible and reduces the diesel consumption of the station.

The research activities presented in Chapter 9 develop a comprehensive understanding of the knowledge and perceptions of the Australian Antarctic community towards hydrogen energy and related technologies. Four specific goals are defined to direct the research efforts – to:

1. Identify the current levels of knowledge about and perceptions of hydrogen energy technologies within the Australian Antarctic community, focusing on upper-level decision makers in the community.
2. Identify potential drivers for or barriers to the implementation of hydrogen technologies in the community, based on the hydrogen-related perceptions of the community members.
3. Determine if hydrogen energy technologies are appropriate solutions for the community, based on the values, culture and objectives of the community.
4. Capture knowledge and experience from other efforts around the world to implement hydrogen energy technologies to provide a broader perspective of the current drivers for and barriers to the use of hydrogen energy technologies in society – particularly their use in remote areas.

Chapter 10 presents an integrated discussion of the preceding three chapters, and evaluates the outcomes of the three different sections of 'experiments' undertaken in the thesis, identifying the cross-cutting themes and key outcomes for the research. The discussion builds on the detailed discussion of the specific results completed independently in each of the three sections.

Chapter 11 presents the framework for a generic 5-10 year strategy and action plan that can be used by Antarctic communities to increase the sustainability of energy resources at their stations. It also describes actions to take to understand energy usage at the stations and to gain access to renewable energy resources for energy generation. Six specific recommendations are presented for Antarctic communities to consider today if they are motivated to access more sustainable energy services. The framework developed in this chapter has subsequently been used to develop a strategy for a member of the international Antarctic community as a research consultancy.

Chapter 12 presents the overall research conclusions. The chapter builds on the detailed conclusions from the specific results completed independently in each of the three sections.

Nine appendices are included at the end of the thesis, presenting conference papers, background materials on the computer simulations in Chapter 8 and community consultation work from Chapter 9, and a development proposal for future work.

1.5 Influencing and testing the research outcomes

The research project was undertaken in a time of significant change for issues relevant to energy use in Antarctica. High profile actions such as the entry into force of the Kyoto Protocol in 2005 [6], for example, raised public awareness and influenced government policies around the globe with respect to the sustainability of energy issues. This influence indirectly impacted perceptions and policies within the Australian Antarctic community over the course of the research. In a more local context, the energy systems used by the Australian Antarctic community have changed over the course of the research with the commissioning of wind turbines at Mawson station in 2004 [7], the cancellation of one of the three planned wind turbines in 2006, and the launching of a hydrogen demonstration project (as a direct result of this research project) in 2003 [8]. These individual projects have shaped the understanding and attitudes of the Antarctic community with regards to the specific technologies and sustainable energy usage in general.

These changes have the potential to influence the continual relevance of the results of the thesis. However, many outcomes remain independent of these short-term influences, and the techniques developed for analysis in the thesis, both the technical and social experimentation, aim to minimise the effects of these changes on the research results. Some of the results of technical analysis, for example, are based on projections of where operations and technologies will be in the future and so will remain independent of short-term changes to the energy systems used at the Antarctic stations. The technology-people interface issues identified within the Antarctic community in the social experiments may remain consistent or change with contemporary issues, but the results will provide examples for identification and analysis of issues in the future, and the results and methods can guide other communities around the world.

During the course of the research, a number of opportunities arose to apply and test the outcomes from the research in real-world situations. These external projects delayed the completion date for the research project by approximately two years in total, but did provide invaluable feedback on the research methods and outcome, and were compelling and relevant opportunities to generate practical results from the academic activities.

The three most significant outcomes for the research, which were converted into genuine and external projects during the course of the research, include:

1. The Mawson Hydrogen Demonstration Project, which secured AUD$500,000 from the Australian government as a result of efforts in the research thesis, for a small pilot wind-hydrogen system at Mawson station. The project was managed by the Australian Antarctic Division, but did include small consultancy projects for the University of Tasmania [8], and provided useful information and feedback on processes and social issues influencing the development of novel energy technology projects in the Australian Antarctic community.
2. An ~AUD$50,000 consultancy project to develop a "sustainable energy technology evaluation & implementation strategy" for the Antarctic research program of a northern hemisphere nation. This project provided an opportunity to apply the preliminary version of the strategy presented in this thesis and gain feedback on its relevance to Antarctic communities and other programs.

3. the ~ AUD$2 million "NordSESIL" project which will build on one of the major outcomes from the research thesis with the development of a communication and knowledge sharing network in the Arctic region [9]. The project will commence in September 2007 with three years funding from the Nordic Energy Research organisation, a component of the Nordic Council of Ministers, and in-kind contributions from industry, government and educational institutions in the Nordic region. The project will be based at the UN Environment Programme's Centre for Energy, Climate and Sustainable Development, the UNEP Risoe Centre (URC), in Denmark. The project was one of twelve projects supported in the 2007-2010 funding round, competitively selected from over 120 original applicants. The project proposal was conceived by the author, and developed in collaboration with the URC after the author approached them with the project during a private trip to Europe in 2006 to secure support and partners for the project concept. The author will commence employment with the URC in September 2007 as the manager of the network [10].

The author was also active with many conference publications aimed at raising awareness of energy issues and the relevant outcomes of the research with appropriate audiences. Publications were presented within the Australian and international Antarctic operations community, the energy research and development community, and also to broader audiences as an application of the research outcomes to strengthen and diversify the interface between people and energy technologies. A range of briefings and information sessions were also prepared for Tasmanian and Australian government audiences. The practical outcomes embodied in the three main projects above, however, are the most relevant and satisfying for the author, and the projects are the best testament to the value and viability of the research outcomes and multi-disciplined approach and the associated research methodology.

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Chapter 2. Energy and Society

This chapter provides a broad introduction to the characteristics and importance of energy systems in modern society and the issues that influence the sustainability of energy services for all sections of the human population. Components include analysis of the importance and sources of energy, examination of the problems that exist with conventional energy systems and the subsequent need for changes, and identification of the actions and strategies that are available to make energy systems more sustainable. The chapter concludes with a brief review of the future of energy systems using renewable energy technologies and novel methods of storing energy.

2.1 A brief review of global energy use and modern society

Energy is essential for human life – to enable the most basic of tasks such as cooking, heating and lighting, or to power the devices, vehicles and industries of the developed world. Modern forms of energy can also dramatically increase human capabilities and opportunities in many ways: enhancing agricultural and industrial productivity; providing light for education, employment or recreation; transporting food, water, waste, people or produce; enabling improvements in medical care or food quality; and facilitating communications and computer operations .

Humanity's demand for energy is continually growing due to the increasing human population, and the increasing proportion of people who are living the energy-intensive lifestyles that are prevalent in the 'developed' world. In the 20th century alone, the human population quadrupled (to approximately 6 billion people) while primary power consumption increased 16-fold (to approximately 12 terawatts) [1].

Although humanity is embracing modern energy systems and enjoying the benefits that they offer, these benefits are being extracted at a growing cost to the natural environment and to current and future generations of the global population. Resources are being consumed until exhausted, ecosystems are being polluted or destroyed, and long-term climate changes and negative impacts on human health are emerging as probable consequences of global energy usage. The long-term stability, viability and prosperity of human civilisation will be negatively affected if current practices are maintained [2-4]. In addition, more than half the world's population living in rural areas still has no access to modern forms of energy – a clear failing of conventional energy systems to meet the wide variety of human energy needs.

With continued growth in existing energy markets, and global efforts to expand access to modern energy services such as through the Millennium Development Goals (MDGs), a clear need has emerged to meet the energy demands of the diverse communities of this planet in a more sustainable manner [5, 6]. Such sustainability must be measured in terms of the impacts of energy system choices on natural resources, the natural environment, and the culture of the communities that the energy systems ultimately serve [7, 8].

The following sections examine further the importance of energy in modern society, review the characteristics of conventional energy systems and the subsequent need for change, and identify a range of actions and strategies to make energy systems more sustainable.

2.2 *The importance and sources of energy in modern society*

The availability of reliable, flexible and extensive energy systems is an essential element of modern society, with obvious roles in health, welfare, education, recreation, agriculture, industries, and the security of any community.

Energy is also central to economic development, and a clear correlation exists between energy consumption and living standards within a community. This viewpoint is a foundation stone in the operations of many international organizations such as the World Bank Group (WBG), and the United Nations' Industrial Development Organisation [9] and Development Program (UNDP) [9-11]. Further analysis has illustrated that sharp increases in living standards can be achieved (from a life without modern energy) if energy services are made available to support consumption of 3-6 kW per person. Additional but moderate improvements to living standards can be further achieved by increasing energy availability to 6-7 kW/person, or further increasing availability to 8 kW/person and above. However, at this upper limit, living standards have been shown to peak with consumption levels so that no further improvements can be achieved [12]. Approximately 2 billion people around the globe, or half the world's population, do not have access to even the minimum level of energy services, posing a significant challenge to the broader efforts to address the MDGs [4, 13]. The UN's 2006 'progress report' on the MDGs, however, indicates that important progress has been made towards the Goals and the success is due in part to improved access to energy services in the developing world [14].

Of the 12 TW (approximately) of power that the global population currently consumes, a very large proportion is drawn from non-sustainable fossil resources. Estimates range from 85% to 95%, with the total global consumption drawn from six primary energy sources: petroleum (44%), natural gas (26%), coal (25%), hydroelectric power (2.5%), nuclear (2.4%), and non-hydro renewable energy (0.2%) [1, 15]. International Energy Agency figures (quoted in [15]) suggest that biomass provides (on average) 33% of the energy needs in Africa, Asia and Latin America, and as much as 80% to 90% in the poorest countries of these regions.

The end applications of this energy use can be separated into five major sectors: industry, transportation, agriculture, commercial and public services, and residential. The current trends in developing countries, by far the smallest users of energy per capita, have the greatest use of energy in the residential sector, followed by industrial uses and then transportation. An opposite trend exists for developed countries, where transportation consumes the largest amount of energy, followed by industrial and then residential consumption [15].

2.3 *Modern energy systems and the need for change*

In meeting approximately 90% of global energy needs, the fossil fuels such as coal, oil, and natural gas are the foundations of conventional energy systems. Over the past century, they have enabled a significant proportion of humanity to access a versatile, convenient, relatively cheap, and extensive supply of energy.

However, a number of clear motivations are emerging for humanity to develop independence from, or at least much less dependence on, these finite and unsustainable fossil fuels. These motivations can be broadly grouped into the categories of local and global environmental impacts of energy systems, human health and welfare, access to and the availability of energy services for communities, and the security of supply of energy services in the future.

Ultimately, the continuation of humanity's high level of dependence on fossil fuels is unsustainable and will lead to critical failures in energy systems, long-term and severe impacts on the Earth's ecosystems, and deprive future generations of resources. These motivations are examined in more detail below, followed by analysis of a range of actions that could be implemented to reduce the dependence of communities on fossil fuels.

2.3.1 Motivation 1: Local and global environmental impacts

The use of fossil fuels for energy generation results in a broad range of environmental impacts that can have negative and persistent consequences for local and global ecosystems. These impacts can occur as damage to local environments during the extraction of raw materials, from the waste materials generated during the processing and refining of raw materials, as a consequence of the transport of raw or processed fuels (including accidental loss of cargo), or ultimately as a result of the combustion of fossil fuels for energy production. These impacts can be clearly visible, such as physical destruction of local environments (e.g. open cut coal mining) or less obvious but equally damaging such as the contamination of land, waterways and the atmosphere with raw or processed materials or combustion by-products.

The potential to induce significant changes in the global climate as a consequence of carbon dioxide emissions from fossil fuel combustion is now a high profile international issue. The development of the United Nations' Framework Convention on Climate Change and the subsequent entry into force (in February 2006) of the 'Kyoto Protocol' is a clear example of the significance and magnitude of the impacts that past, present and future fossil fuel use are expected to have on the planet [16, 17]. A core component of the 'concerns' relating to the formation of the Protocol is the increase in global atmospheric carbon dioxide from ~275 to ~370 parts per million (ppm) over the past century. Unchecked, it is expected to pass 550 ppm this century and thereby exceed all known previous levels and result in major changes to global climate patterns [1].

2.3.2 Motivation 2: Human health and welfare

The release of pollutants into local environments as a consequence of biomass or fossil fuel use, either from fuel leakage or as emissions from refining or combustion, has been extensively proven to lead to reduced human health, including respiratory illnesses (particularly asthma in children) and cancer. These illnesses impact the quality of life of the individuals affected and also impact society more broadly through reductions in productivity (e.g. parents leaving work to care for ill children) and increased health expenses. The comprehensive "World Energy Assessment: Energy and the challenge of sustainability" produced in 2000 by the United Nations Development Programme, United Nations Department of Economic and Social Affairs, and the World Energy Council includes a fifty-page review of energy-related health issues [18].

The longer-term threats of potential climate changes and more frequent occurrence of extreme weather events will also impact human health and welfare. For example, storms, tornadoes, and other extreme weather events substantially impact communities and can lead to physical injuries; damage to the Earth's atmosphere could lead to increased cancer risks for individuals while impacting the rainfall patterns that enable the supply of fresh water and agriculture for major cities.

In 2003, the long-term threats to national security embodied in climate change predictions were investigated by Schwartz and Randall for the United States (US) Department of Defence. The report conclusions included that it was 'quite plausible that within a decade the evidence of an imminent abrupt climate shift may become clear and reliable'. If such a shift did occur, they concluded that the US would need to take "urgent action (including diplomatic action) to prevent and mitigate some of the most significant impacts". Large population movements are also viewed as inevitable and learning how to manage those populations, border tensions that arise and the resulting refugees will be critical. New forms of security agreements dealing specifically with energy, food and water will also be needed. In summary, they advise that while the US itself will be relatively better off and with more adaptive capacity, it will find itself in a world where Europe will be struggling internally, large numbers of refugees will be "washing up" on its shores and Asia will be in serious crisis over food and water. "Disruption and conflict will be endemic features of life" [19]. The climate change scenario used as the foundation for the report was viewed as 'unlikely but plausible', and serves to demonstrate the significant impacts to health and human welfare that may result from the continued use of fossil fuels.

2.3.3 Motivation 3: Access and availability

High levels of access to and availability of fossil fuels have been core components of the economic and social development of the modern and industrialized world. As outlined above, access to a minimum level of energy (3-6 kW/person) is essential to enabling economic development and improvements in quality of life [12]. Although fossil fuel-based energy systems have been successful in meeting the energy needs of developed and developing nations, they have failed to provide viable solutions for energy supply to a substantial proportion of the global population.

A Business Council for Sustainable Energy (BCSE) report on increasing access to energy in developing countries estimates that over 1.64 billion people worldwide (99 % of them in developing countries) live without access to electricity. Four out of five of those are in rural areas and 80 % are from South Asia and sub-Saharan Africa. Even in Latin America, where total electrification is much higher at 86 percent, nearly half of those in rural areas still lack access to electricity [20]. The report quotes the International Energy Agency's "World Energy Outlook 2002" in stating that "a lack of electricity exacerbates poverty and contributes to its perpetuation, as it precludes most industrial activities and the jobs they create" [21]. Conventional energy systems have therefore clearly failed to meet the basic rights of access for many of the world's disadvantaged and economically poor, and alternative technologies and approaches to providing energy services must be considered if global levels of access to energy are to increase.

Consumers in developing countries who are 'fortunate' enough to have access to electricity services, however, are commonly faced with power 'outages' as power system failures are endemic. Transmission and distribution line losses in developing countries often run as high as 20 to 30 % due largely to inadequate maintenance and investments in distribution systems. The financial viability of electric utilities in developing countries also remains constrained by improper billing, lack of payment, unauthorized connections and continued subsidies that often benefit customers who have the ability to pay [20].

Addressing the obvious global inequalities in the access to and availability of modern energy systems formed the focus of the 2004 World Energy Congress [22]. I was selected to attend this event as a *Youth Symposium Fellow* and presented a paper on the selection of appropriate energy systems for communities [23]. Components of the paper have subsequently been included in relevant areas of this thesis.

2.3.4 Motivation 4: Security of supply

Fossil fuels, particularly oil, are finite resources that are not equally distributed amongst the many energy consuming nations of the world. Coupled with continually increasing global demand for fossil fuels and the depletion of resources over the past century, these two factors are leading to increasingly acute concerns about the guaranteed supply of fossil fuels in the short and long-term.

An analysis of the "BP Statistical Review of World Energy" in 2004 concluded that "analysis of this year's oil production statistics leads to the conclusion that declining production and depletion is now a significant influence and that rapid production increases are sustainable in only a limited number of countries" [24]. Production peaks were specified to have already occurred for North America (1997), Asia-Pacific (2000), OECD (1998), and potentially in Latin America (2002). This circumstance was seen to give a great deal of political and financial leverage to those countries that do have expansion potential. Skrebowski postulates that "if the world is to get the oil production it is likely to require, a great deal of additional investment will have to take place" [24].

Bentley defines these circumstances as placing conventional oil supply at a 'political' risk. This is because the sum of conventional oil production from all countries in the world, except the five main Middle-East suppliers, is near the maximum set by physical resource limits. Should Middle-East suppliers decide to substantially curtail supply, the shortfall cannot be replaced by conventional oil from other sources [25].

Bentley proposes that the world's conventional oil supply will also soon be at 'physical' risk as the Middle-East countries have only little spare operational capacity, and this will be increasingly called upon as oil production declines elsewhere. Bentley suggests that output could be raised, but only to a limited extent, if large investments (as identified by Skrebowski) are undertaken in Middle-East production. However, if demand is maintained, and if large investments in Middle-East capacity are not made, global oil shortages in the near term are predicted.

Even with large investments, resource limits are expected to force Middle-East production to decline fairly soon, and hence also global conventional oil production. The date of this resource-limited global peak depends on the size of Middle-East reserves, which are poorly known, and unreliably reported. Bentley's assessment of the 'best estimates' puts the physical peak of global conventional oil production at between 5 and 10 years in the future (2007-2012) [25]. This is neither the first, nor the only, predicted peak in global oil production, but it is widely supported by experts and analysts from industry and government around the world [26-31].

It is interesting to also note that Bentley specifies a partial exception for Iraq with respect to declining production capability, but evaluates that even there, significant delays would be faced before prospects are confirmed and infrastructure could be installed [25]. Since the early-2002 timing of the publication, circumstances in Iraq have altered dramatically and continuing conflict and unrest should be expected for decades to come as an outcome of the US-led and 'not UN-endorsed' invasion in 2003 [32]. Doubts about the true motivation for the military action and the practical outcome of the invasion and occupying force, particularly with regards to protecting and expanding oil production infrastructure, serve to effectively demonstrate the serious and multifaceted issues surrounding 'security of supply' for fossil fuel resources – particularly oil.

Crude oil is not the only resource generating concerns about the security of supply. Di Mario *et al.*'s analysis of Europe's dependence on external energy resources highlights that 60% of the world's natural gas resources belong to Russia, thereby posing one of the 'political risks' characterized by Bentley [33]. Bentley also comments about conventional gas resources, assessing the world's original endowment as 'probably' equivalent in energy terms to its endowment of conventional oil. Since less gas has been used so far compared to oil, the world will turn increasingly to gas as oil declines. But the global peak in conventional gas production is already in sight, in perhaps 20 years, and hence the global peak of all hydrocarbons is likely to be in about 10 or so years (2012) [25].

Although the situation is less bleak for coal with respect to the size and global distribution of resources, many of the higher quality reserves have been consumed and greater environmental impacts will result from the use of lower quality reserves . Liquid transport fuels to replace those derived from oil can also be produced from coal, although the process is less energy efficient than conventional oil refining methods and subsequently has found very limited commercial support to date (except in South Africa) [34, 35].

The potential impacts of reduced security of energy supply include higher energy costs, short-term shortages leading to disruption of commerce, geo-political instability and conflict over resource availability, extraction of reserves from more environmentally sensitive or expensive regions, and ultimately, long-term price increases following the supply-demand laws of economics [36, 37]. Many of these impacts have been illustrated to some degree in the past few years, particularly in the United States, which is the world's highest per capita consumer of energy.

These four issues - local and global environmental impacts, human health and welfare, access and availability of energy services, and the security of energy supply –apply to energy-using communities of all sizes, and clearly indicate that changes need to be made to the conventional energy systems serving society. How and when change should occur is now a question of considerable debate. Crabtree *et al.*. commented in 2004 that "although it is impossible to predict when the fossil fuel supply will fall short of demand or when global warming will become acute, the present trend of yearly increases in fossil fuel use shortens our window of opportunity for a managed transition to alternative energy sources" [38]. Although Crabtree's 'window' to affect change in humanity's fossil fuel-dependent energy systems is continually decreasing, it is never too late to start.

The following section examines the major categories of actions that could be undertaken to enable the necessary changes in modern energy systems.

2.4 Actions and strategies to make energy systems more sustainable

Sustainability has been defined as an attempt to provide the best outcomes for the human and natural environments both now and into the indefinite future. It relates to the continuity of economic, social, institutional and environmental aspects of human society, as well as the non-human environment. It is intended to be a means of configuring civilization and human activity so that society, its members and its economies are able to meet their needs and express their greatest potential in the present, while preserving biodiversity and natural ecosystems, and planning and acting for the ability to maintain these ideals in a very long term. Sustainability affects every level of organization, from the local neighborhood to the entire planet [39].

The publication of "Our Common Future" (also known as the Brundtland Report [8]) by the UN World Commission on Environment and Development (WCED) in 1987 was designed to capture the spirit of the United Nations Conference on the Human Environment (the Stockholm Conference, 1972 [40]) which had introduced environmental concerns to the formal political development sphere [41]. The Report's targets were multilateralism and interdependence of nations in the search for a sustainable development path. The report placed environmental issues firmly on the political agenda and discussed the environment and development as one single and important issue [41].

The Report also provided an effective (and now widely used) definition for 'sustainable development' that links the concepts of sustainability and human development. This definition was subsequently adopted by the Agenda 21 program of the United Nations [42].

> *sustainable development*: "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [8].

Any effort to improve the sustainability of the energy services used by humanity – on a local or global scale - must take these terms and concepts into consideration. As further defined by the 1995 World Summit on Social Development [43], the concept of sustainable development should be applied in an energy supply context as "the framework for our efforts to achieve a higher quality of life for all people". Within this framework, "economic development, social development and environmental protection are interdependent and mutually reinforcing components" [4, 43].

In 2001, the United Nations Development Program (UNDP) – in collaboration with the UN Department of Economic and Social Affairs and the World Energy Council –

prepared the "World Energy Assessment: Energy and the Challenge of Sustainability" . The Assessment affirms that solutions to the many urgent problems are possible and that the future is much more a matter of choice than destiny. It analyses the social, economic, environmental and security issues linked to energy supply and use, and assesses options for sustainability in each area. Among the many issues discussed are: renewable energy technologies; advanced energy supply technologies; rural energy in developing countries; energy and economic prosperity; and energy policies for sustainable development.

As described by UNDP Administrator Mark Malloch Brown in a follow-up report, the Assessment concluded that "we *do* have the resources and technological know-how to rise to the challenge of energy that supports sustainable development" . Malloch Brown commented further that "doing this will require major shifts in policy – it will not simply happen on its own".

The WEA document and Malloch Brown's comments suggest two critical points in relation to the addressing the faults with conventional energy systems:

1. Technical solutions do exist to make the energy systems used by conventional society more sustainable, and
2. Solutions to achieve change will require more than purely technical solutions.

The follow-up report by the UNDP, "Energy for Sustainable Development: A policy agenda" makes a substantial contribution to understanding the non-technical actions that could be pursued, particularly major policy shifts, and offers "informed guidance on the next steps, on how to shape public policy so that it accelerates the growth of energy systems that support sustainable development".

Recognizing that global climate change is an important and high profile issue of concern in any discussion about energy systems and sustainability, the 2001 WMO/UNEP Intergovernmental Panel on Climate Change (IPCC) 3rd Assessment Report is also a relevant source of information on potential actions. The report analyzes a range of actions to address global climate change through the limiting of greenhouse gas emissions [2]. The UN Environment Program (UNEP) report, "A simplified guide to the IPCC's "Climate Change 2001: Mitigation" " provided a relevant and comprehensive overview of the report [44]. The fourth Assessment Report is being released in 2007 and provides further detailed analysis of the impacts of and potential solutions to global climate change. The Assessment Report from Working Group III focuses on methods to mitigate climate change. A pre-copy edit version was available in August 2007 [45].

The following section provides a summary of the major categories of technology and/or policy-based actions and strategies that can be pursued to identify and implement sustainable and technically viable energy solutions.

2.4.1 *Use cleaner conventional energy systems, including capture and sequestration of emissions.*

Capturing the harmful environmental emissions from conventional energy systems, particularly carbon dioxide, and storing or 'sequestering' the material is one option to reduce the release of emissions to the atmosphere. This area of research is currently attracting considerable attention from conventional energy industries. As an 'output'-focused method of reducing environmental impacts, it is seen to enable the use of much of the conventional infrastructure installed in societies, and facilitate the 'sustainable' continued use of more abundant fossil fuel reserves (such as coal). However, the development of effective methods of capturing and storing exhaust emissions remains a challenge for many types of energy production [46, 47].

Other methods of reducing the emissions from conventional energy systems include removing impurities from fuels prior to combustion (e.g. removal of sulphur from diesel fuel) or filtering exhaust emissions to extract particulate and chemical contaminants [48-50].

Whilst these actions to reduce emissions from conventional energy systems are obviously steps in the right direction to reduce environmental impacts, they are not genuinely sustainable solutions due to their continued dependence on finite resources. They also fail to address the issues of security of energy supply or improving access to energy systems.

2.4.2 *Reduce energy use through efficiency improvements*

Lowering a community's demand for energy inherently improves the sustainability of their energy systems by reducing the consumption of resources and the extent of emissions and impacts. Improving the efficiency of all or any one element of an energy system (i.e. energy generation, transmission/distribution, and/or end-use) is one proven technique to achieve reductions in total energy demands. Conventional energy systems offer innumerable opportunities for efficiency improvements, ranging from the large-scale energy generation plants of energy companies to the many devices and vehicles of end-users. Many studies into industry and consumer energy efficiency programs have shown that the cost of implementing energy efficiency improvements can be recouped in acceptable, if not economically attractive, periods of time [51-53].

Chow *et al.* provided a compelling example of the potential for improvements in energy efficiency, where countries of similar technical development and gross national income per capita (GNI/pop) have reasonably different levels of energy consumption [15]. The examples of Norway and Japan are presented with energy consumption per capita of 250 GJ in Norway and 150 GJ in Japan and GNI/pop of US$34,530 and $35,620 respectively. The suggested reason for the difference in energy use is Japan's greater dependence on imported energy resources provides stronger incentives for energy efficiency, while Norway has high availability of relatively inexpensive hydroelectric power and consequently has reduced demand for energy efficiency [15].

2.4.3 Introduce alternative primary energy sources

Although fossil fuels are responsible for providing the vast majority of humanity's energy demands (85%-95%), a number of alternative primary energy sources are utilised in modern energy systems, including hydroelectricity and other forms of renewable energy and nuclear power [1, 15].

A wide range of renewable energy resources can potentially be harnessed by energy consumers, including wind power, solar power (thermal and photovoltaic), wave, tidal, hydro, micro-hydro, geothermal, and sustainable biomass energy crops. Photovoltaic (PV), solar thermal and wind turbine technologies have matured considerably in recent decades and are now commercially competitive in a number of applications.

The advantages offered by renewable energy technologies include the production of energy (electricity or heat) using a diverse range of sustainable and local primary energy resources, and reduction (or elimination) of direct environmental emissions such as carbon dioxide (although the source of the energy used for the production of the renewable energy infrastructure may have associated environmental emissions).

The primary disadvantages with renewable energy technologies include the higher cost of energy (in comparison to most conventional energy systems), the intermittent nature of the primary energy resources requiring energy storage mechanisms, and a general lack of success in powering conventional vehicle fleets with energy derived from renewable sources [54]. Dell and Rand provide a comprehensive overview of the role of energy storage technologies in achieving global energy sustainability [55].

Nuclear power is another alternative primary energy source that could be used to replace carbon-based fuels for transport and stationary power applications. Interest groups regularly present arguments for and against a resurgence of the international nuclear power industry. Supporters cite advantages such as the availability of relatively cheap and carbon-free power. However, issues such as public perception about the safety of reactors and nuclear fuel/waste materials, the availability of appropriate long-term waste disposal facilities, and the proven failure of such systems to meet the energy needs of many communities continue to dampen enthusiasm for nuclear power [56-58].

Achieving reductions in total energy demands such as through increased energy efficiencies would enable the current installed capacity of non-fossil fuel energy systems to meet a greater proportion of global energy demand. However, improvements in energy efficiency would realistically only slow the growth rate of energy demand and additional non-fossil fuel generating capacity is required to increase the proportion of global energy demand that is met from non-fossil sources.

Chow *et al.* noted that no primary energy source and its associated technologies are completely free of environmental and other drawbacks. They suggest that in order to minimise environmental damage relative to the benefits of energy consumption, a sustainable, environmentally-benign energy system, or at least the transition to one, will involve a heterogeneous portfolio of renewable primary energy resource [15].

2.4.4 Diversify energy carriers and fuels

Although humanity currently uses six different forms of primary energy (see section 2.2), energy consumers generally 'receive' this energy using two dominant forms of energy carrier – electricity for stationary energy demands, and petroleum-derived fuels (e.g. diesel or gasoline/petrol) for transport applications. Other common but less versatile energy carriers include chemical batteries (such as for mobile devices), natural gas as a fuel for vehicles or heating, and reticulated water heating systems that may capture waste heat from industrial processes or natural (geothermal) heat sources.

Increased use of energy carriers that enable more effective utilization of alternative energy sources or wasted energy in existing systems, such as the example of reticulated water heating systems, can improve the performance and sustainability of energy systems. In addition, a variety of alternative and innovative energy carriers have proven to be viable for certain applications, including the production of hydrogen from hydrogen-rich source materials. This thesis extensively examines the concept of using hydrogen as an energy carrier.

Alternative energy carriers, particularly hydrogen, can also enable the greater utilization of renewable primary energy sources by serving as energy storage mechanisms. Turner has reviewed the ability of renewable resources to provide all of society's energy needs, using the United States as an example, including the use of hydrogen as an alternative energy carrier and energy storage mechanism [59]. The use of hydrogen as an energy storage mechanism is also examined in detail in this thesis.

2.4.5 Use alternative technology paths and energy system designs

Conventional energy systems are not only highly dependent on fossil fuel sources, but also on a generation of energy conversion technologies and energy system designs that emerged and matured in parallel with the development of the global hydrocarbon economy.

The technologies most closely tied to fossil fuels are the internal combustion engine (ICE) and other combustion-focused energy generation systems (e.g. coal-burning steam turbines in power stations). These technologies are constrained by the laws of thermodynamics and the Carnot cycle to relatively low efficiencies (approximately 30%) for conversion of primary energy to mechanical power. The combustion of fossil fuels results in the release of chemical and particulate pollutants which have negative impacts on the environment and human health.

The energy system design most related to fossil fuels is that of large-scale and centralised infrastructure which utilises economies of scale to deliver energy services at relatively low costs. These systems are typified by large power plants (coal, oil, and gas, with contributions from nuclear and hydro) consistently generating substantial amounts of energy for delivery to industrial and residential consumers over long-distance, high-voltage electricity lines.

A range of innovative energy generation and conversion technologies and design concepts are enabling the development of alternative energy systems. Technologies such as fuel cells [60] or Stirling engines [61, 62] enable more efficient conversion of conventional fuels such as natural gas or diesel, with the added benefit of potential for waste-heat capture for space heating. These technologies, and/or alternative primary energy generation systems (such as PV panels integrated into residential buildings) can become the building blocks of decentralised energy systems. Decentralised energy systems can offer greater flexibility and security over conventional centralised systems, can utilise a range of primary energy sources and energy carriers, and are suitable for a wide range of energy demands. In contrast, centralised energy systems remain vulnerable to disruption to the primary energy generation facility (and single fuel supply) and distribution network and have proven to be unacceptable for an important proportion of the human population.

Hoffert *et al.*, in their review of climate change-based motivations for a movement away from the use of fossil fuels, argue that "the most effective way to reduce carbon dioxide (CO_2) emissions with economic growth and equity is to develop revolutionary changes in the technology of energy production, distribution, storage and conversion" [1]. The paper reviews a range of options for achieving reductions in CO_2 emissions, including improved efficiency, de-carbonisation and sequestration, renewable energy sources, fission and fusion, geo-engineering, and roles for alternative energy carriers such as hydrogen.

2.4.6 Change energy usage patterns and behaviour

The actions and thought processes of energy users can have a significant impact on the characteristics and magnitude of consumption for all types and all sectors of energy use. A wide range of actions can be undertaken to reduce energy demand or optimise energy system operations through changes in the patterns of energy use, including 'active' measures intended to directly influence or control user behaviour and 'passive' measures that enable users to make more informed decisions about energy use. Effective examples of both types of measures can be found in the application of 'demand side management' (DSM) to energy systems [63, 64].

DSM encompasses a variety of activities designed to change the level or timing of users energy demand. Eto's paper on U.S. utility programs divided DSM into seven categories. These categories can be easily applied as general principles to all types of energy use and user management, and include: (1) general information to increase customer awareness of energy use and of opportunities to save energy; (2) technical information, including energy audits, which identify specific recommendations for improvements in energy use; (3) financial assistance in the form of loans or direct payments to lower the first cost of energy-efficient technologies; (4) direct or free installation of energy-efficient technologies; (5) performance contracting, in which a third party contracts with both the utility and a customer and guarantees energy performance; (6) load control and load shifting, in which the utility offers financial payments or bill reductions in return for controlling a customer's use of certain energy-using devices (such as electric water heaters and air conditioners) or in return for customer adoption of technologies that alter the timing of demands on the electric system (such as thermal storage); and (7) innovative tariffs, such as time-of-day and real-time prices, price signals that can enhance the effectiveness of other DSM programs. The first five types of programs are intended to promote energy efficiency. The last two types are intended to promote specific load-shape objectives, such as peak-load reduction, load shifting, or off-peak load building [65, 66].

2.4.7 *Implement strategies to enhance the sustainability of activities*

Many conventional energy systems, and social practices in general for that matter, are not sustainable. Improving the sustainability of energy systems will require changes from existing practices and technologies. These changes must be identified, evaluated, and selected, and subsequently implemented.

The UNDP report, "Energy for Sustainable Development: A policy agenda" examines the importance of policies and strategies to ensure that options for actions, such as those identified above, are put into use by communities .

Comprehensive strategies to improve the sustainability of energy systems have been developed on local, regional, national and international levels and include many of the other actions reviewed in the preceding pages. Other components of energy development strategies include specific goals, policy actions to enforce or encourage activity, research and development plans, consumer education efforts, and industry engagement [67-69].

2.5 *A future based on renewable energy and alternative energy carriers*

A key element of many strategies to increase the sustainability of energy systems is greater use of alternative primary energy sources, based on the known environmental impacts of and long-term concerns about the availability of fossil fuels. Leading candidates include wind and solar renewable energy technologies, and nuclear power. These alternative energy sources have relative advantages and disadvantages to one another and to fossil fuels, but most (such as nuclear power) do not address all of the previously identified motivations to move away from fossil fuels.

For this reason, renewable energy technologies are seen by many as the ultimate hope for the future development of sustainable energy systems. However, renewable energy systems also face many challenges, including their intermittent supply and the related demand for effective methods of energy storage, and their currently limited ability to meet transport energy needs.

With the projected movement away from the use of oil (and its derivatives) as a transport fuel due to the environmental consequences and the concerns about lack of supply, there is also a clear need to develop alternative energy carriers. Hydrogen is emerging as a preferred leader amongst these solutions as a global replacement for the oil economy (hydrogen economy), although the other options will serve valid roles in more local markets. Hydrogen is widely regarded as the most viable, flexible and acceptable option from a number of possible alternative energy carriers [59]. Chapter 3 presents a detailed analysis of the use of hydrogen as an energy carrier and the types and status of associated technologies.

In addition to highlighting the importance of energy to modern society and the problems associated with reliance on conventional energy systems, this chapter has outlined the range of solutions available for the development of more sustainable and accessible energy systems. Renewable energy technologies were shown to have great promise and although they face a number of challenges, potential solutions to these issues such as hydrogen storage are emerging. However, consideration of the use of 'renewables' and hydrogen – or any energy technology solutions for that matter – must include analysis of whether the proposed solution is 'appropriate' for the particular needs of the energy-using community that the system will ultimately serve. The outcome of such assessments on the 'appropriateness' of specific energy technologies will influence the type and role of the energy technologies selected. Chapter 5 examines further the issue of identifying 'appropriate energy solutions' and presents a simple approach and methodology.

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Chapter 3. Hydrogen energy and the global energy future

The idea of using hydrogen as an "energy carrier" or energy storage mechanism has existed for over a century, but is now attracting substantial interest as global efforts to develop more sustainable energy system increase in importance and intensity. Hydrogen technologies have been described as 'critical technologies' (ones that can bring about a step function effect in the present state of affairs) in relation to sustainability [1].

This chapter provides a concise overview of the concept of the hydrogen economy and associated basic principles, focusing on the current state of viability (from a user perspective) and the opportunities that exist with hydrogen energy technologies. The material presented demonstrates that hydrogen energy technologies are viable enough for consideration by user communities at this time, but there are still a range of barriers to be overcome.

3.1 What is Hydrogen Energy?

Hydrogen is the most common element in the universe, and is primarily used as a chemical feedstock in a wide variety of industries. However, it is rapidly emerging as a potential candidate to replace oil as the dominant energy carrier in the global energy economy – a global hydrogen economy - and could enable the development of clean and sustainable energy systems.

The 'hydrogen economy' concept involves the use of hydrogen as a means of storing and transporting *primary* forms of energy by generating hydrogen from source materials and then using that hydrogen as an energy storage mechanism or as an alternative fuel.

The potential advantages for any society that uses hydrogen as an energy carrier are considerable, and include local improvements in urban air quality or global improvements in climate-changing pollution emissions through the use of a fuel that has no carbon-based pollutants. Additional benefits could include job creation through the development of new industries and more cost-competitive energy supplies for society and the use of local energy resources to produce vehicle fuels. Scott provides a philosophical vision of a future hydrogen energy economy, with a focus on the delivery of the energy 'services' that are required by society [2]. Other reviews by Midilli *et al.* [3] and Crabtree *et al.* [4] expand on the potential roles that hydrogen technologies could play in the future.

Although pure hydrogen is well suited for use as a fuel due to its high level of chemical reactivity, it is not a primary energy source – it is a common element, but it cannot be extracted or harvested in its pure form and is instead found bonded to other elements. Fossil fuels (hydrogen and carbon) and water (hydrogen and oxygen) are two examples of relatively abundant materials that contain rich sources of hydrogen. In order for hydrogen to be used as an energy carrier or fuel, it must be liberated from these bonding relationships. This process of separation requires the input of primary energy from another source, so that the production of hydrogen becomes a means of storing the original primary energy.

The use of hydrogen as an energy carrier offers two distinct advantages over conventional solutions, including:

1. Hydrogen 'fuel' can be produced from a wide variety of hydrogen-rich source materials using an equally wide variety of primary energy sources. Hydrogen can serve as a storage mechanism and fuel production route for local and renewable primary energy resources, enabling a secure and sustainable energy system.
2. The reaction of hydrogen for energy generation results in practically no emissions beyond water vapour – no carbon dioxide or other greenhouse gas emissions and no particulates. This can substantially reduce the impact of energy systems on the global and local environment and subsequently human health and welfare. (However, in some combustion processes, the burning of hydrogen at elevated temperatures in air results in the production of nitrous oxides; also, any emissions associated with the generation of primary energy used for the hydrogen production must be associated with the hydrogen fuel).

3.2 *A review of hydrogen energy systems*

The use of hydrogen as a fuel requires the development of hydrogen energy systems. Such systems are composed of three essential components – those necessary for the production, the storage (and delivery) and the eventual conversion or use of hydrogen fuel to meet user needs. The overall cycle is presented in Figure 3.1, and a brief review of the processes follows in the following sections.

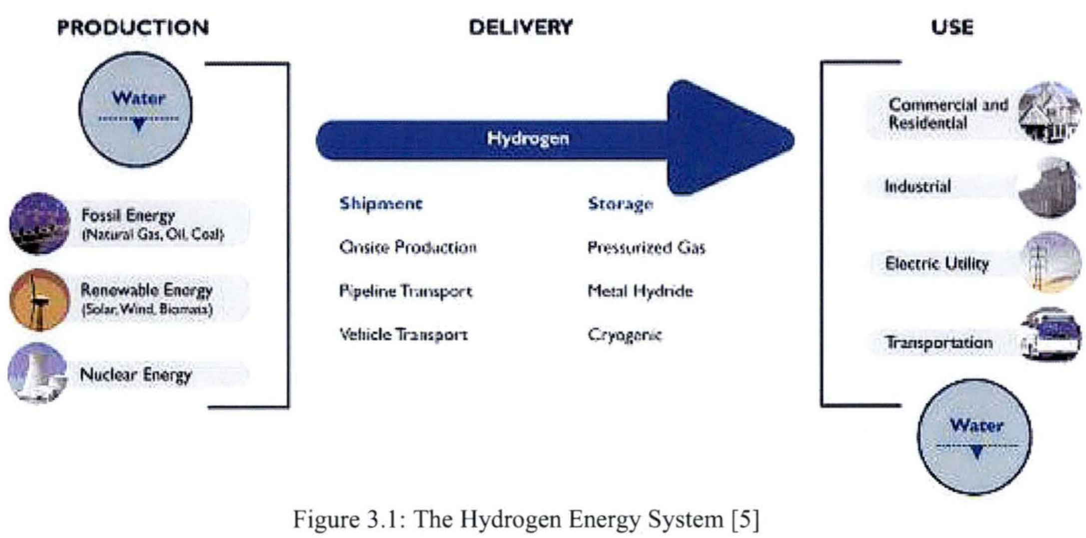

Figure 3.1: The Hydrogen Energy System [5]

It must be noted that the research that is currently being undertaken around the world on the many facets of hydrogen energy is immense in its depth and complexity. The following review provides a very brief overview of the key themes relating to hydrogen energy and identifies relevant resources for details of current research and development activities.

3.2.1 *Hydrogen Production*

As noted above, hydrogen is not a material that can be conveniently harvested in a concentrated form, in contrast to conventional energy resources such as coal, oil and natural gas. Consequently, to use hydrogen as it a fuel it must be produced or generated from hydrogen-containing materials.

Hydrogen can be produced from a variety of source materials using a variety of methods, with the production process consuming external sources of energy. Common source materials include water (H_2O), hydrocarbon fuels (C_nH_{2n+1}), and organic matter such as bio-waste. Methods that currently exist for producing hydrogen from such materials include the use of direct sunlight or biological organisms, electrolysis of water with electricity from renewable (wind, solar, tidal power) or non-renewable (coal, nuclear, natural gas) power stations. Hydrogen can also be produced from fossil fuels by "reforming" or stripping out the hydrogen from the fuel feed. As an alternative to 'producing' hydrogen, some hydrogen-rich materials can be directly consumed to produce energy, as with current conversion technologies (e.g. combustion engines) that run on hydrocarbon fuels and thereby use the hydrogen-related energy in the fuel materials.

Most of the hydrogen currently produced in the world is made from the reaction of steam and methane or natural gas (steam-methane reforming) – although this is based on the use of the hydrogen in large-scale industries with access to natural gas resources. Only a small percentage (4%) is produced by electrolysis of water, potentially using renewable energy. However, the growing demand for small-scale and localised production of hydrogen for use as a fuel is directing research and development (R&D) efforts towards to development of a new breed of hydrogen producing technologies. This may result in a paradigm shift in production methods that favour small-scale, decentralised energy systems – ideally using renewable primary energy sources [6, 7]. Figures 3.2 and 3.3 illustrate two commercially available products for the small-scale production of hydrogen fuel.

Figure 3.2: (left) Proton Energy's HOGEN S Series hydrogen generation systems produce ultra-high purity hydrogen gas using domestic water and electricity connections [8].
Figure 3.3: (right) Intelligent Energy's Hestia technology platform can run on a range of fuels, including ultra-clean, low-sulphur FT diesel fuel (produced from coal or natural gas) [9].

As noted previously, the production of hydrogen converts energy from an initial form into stored chemical energy, and the hydrogen can be subsequently transported.

These processes require some form of storage medium.

3.2.2 Hydrogen Storage

Conventional methods of storing hydrogen include liquid or compressed gas technologies – these systems have decades of proven service in conventional industries. Emerging technologies include absorption onto metal hydride (MH) or carbon-based storage materials and other application-specific concepts. These can be single or multiple-use vessels. The conventional hydrogen storage technologies are challenged to store enough hydrogen in a convenient physical size to compete with traditional liquid fuels such as petrol/gasoline, and efforts are focusing on using higher compression levels or lightweight tanks. The emerging technologies, such as in Figure 3.4 below, show great promise, but still suffer from a number of challenges, including high relative cost, fabrication difficulties, and limited lifecycles. Considerable research resources around the world are dedicated to improving hydrogen storage capabilities as this is currently one of the greatest impediments to the large-scale penetration of hydrogen energy systems into mainstream use [10-12].

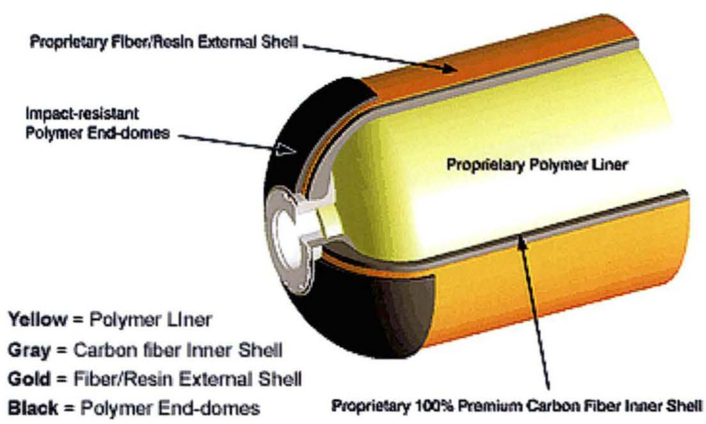

Figure 3.4: Trishield ™ Composite Hydrogen Storage Cylinder by Qantum, the first high-pressure hydrogen storage tank of 700 bar technology capacity to receive German technical certification [13].

In additions to advancements in materials science and production techniques by researchers and manufacturers in the different categories of hydrogen storage technologies, leaps in hydrogen storage system performance are being achieved through innovative cross-fertilisation between the categories. For example, in 2005 Mori *et al.* published details of a "high-pressure metal hydride tank" [14]. The tank was based on a 35 MPa cylinder vessel, with an integrated heat-exchanger module including hydrogen-absorbing alloy. Its advantage over high-pressure cylinder vessels is a larger hydrogen storage capacity in the same physical volume (7.3 kg in 180 L tank volume). The subsequent vehicle cruising range specified for a car is 'about 2.5 times longer than that of the same volume 35 MPa cylinder vessel system'. While the conventional hydrogen-absorbing alloy tank has problems in charge and discharge process, the hydrogen charging rate of this system is equal to a 35 MPa cylinder without external cooling facility. The authors propose that high-pressure MH systems will be a realistic way to obtain adequate cruising range over travelling distances that are realistic to conventional consumers (e.g. 700 km).

3.2.3 Hydrogen Conversion

As with hydrogen storage, conventional and emerging technologies exist for the conversion of hydrogen fuel into more 'useful' forms of energy. Conventional methods include all current technologies suitable for the combustion of traditional fuels (engines, turbines, barbeques, *etc.*) with slight modifications to their operation, component materials, and fuel supply. Emerging technologies include the catalytic conversion of hydrogen for heat production, or the electrochemical conversion of hydrogen to electricity via fuel cells. Fuel cells have a long history of development, and specialised use in applications such as satellites and space vehicles, but are now on the cusp of developing commercially viable markets. They do deserve further review for their significant potential to revolutionise future energy systems.

Fuel Cells: an innovative alternative for energy generation from hydrogen; A fuel cell works by converting chemical energy into electrical energy and heat. As with conventional batteries, fuel cells use a cycle of chemical reactions between positive and negative electrodes to produce an electric current. Unlike batteries, fuel cells are supplied by fuel - commonly some form of hydrogen - and need to be refuelled rather than recharged. A range of hydrogen-rich fuels can be used depending on the design and operating parameters of the cell, including pure hydrogen, methanol, natural gas and gasoline or diesel fuels.

In a typical hydrogen fuel cell, the hydrogen fuel is supplied to a cathode, or negative electrode, and air is passed into an anode, or positive electrode. The porous metal electrodes act as catalysts to speed the reactions of hydrogen gas from the fuel and oxygen from the air with the electrolyte, a pool of chemicals bathing the electrodes. At the anode, the oxygen reacts with water in the electrolyte to form hydroxide ions. At the cathode, the hydrogen fuel reacts with the hydroxide ions to form water, releasing two electrons per hydrogen molecule.

The released electrons flow through an external circuit. As with other forms of electricity generation, this electrical current can be applied to produce work. The chemical cycle also produces heat.

There are five basic types of fuel cells, which are characterised by fuel type (pure H_2 and/or reformed hydrocarbons), the operating temperature (approximately 50-1200 °C), the cooling method (air or reticulated water) and the component materials and fabrication methods [15].

The current status of fuel cell technology is that a range of commercial products is available to suit a diverse range of applications and energy demands covering a spectrum from milliwatts to megawatts of electricity. Many developmental and pre-commercial systems are being tested for availability in the near future. Cost, lifecycle issues, fabrication techniques, and field trialling are some of the present challenges to further market release.

3.3 *Potential applications of hydrogen energy technologies*

The wide varieties of energy conversion technologies that are linked to the use of hydrogen as an energy carrier enable a diverse range of potential applications for hydrogen energy. Hydrogen technologies are capable of replacing conventional energy systems in conventional applications, and providing opportunities for innovative use. The following sections examine the general applications of hydrogen energy technologies in the broad sectors of:

1. Transport
2. Stationary energy, including remote communities
3. Mobile devices

3.3.1 Transport sector applications for hydrogen energy technologies

The global consumption of energy in the transport sector is significant – particularly in the 'oil hungry' OECD countries where it accounts for 60% of the total oil consumption. In the United States, for example, transport accounts for 25% of the total national energy use with practically all this transport energy sourced from fossil fuels. Energy use in transport is subsequently a large component of the global oil consumption of 80 million barrels per day (2003 figures) and the total global energy demand. Transportation (and industry) is projected to be the major growth sector(s) for oil demand until 2030. On a global basis, the transport sector is expected to contribute about one-half of the total increase in oil use between 2003 and 2030 [16].

As there are currently no alternative fuels that compete widely with oil, there is a clear need to develop viable replacements for oil as a vehicle fuel. The opportunities presented by the use of hydrogen as a fuel are being soundly seized by almost all of the major vehicle manufacturers, and new products are regularly demonstrated around the world that include hydrogen technologies in some form.

The flexibility of hydrogen energy systems enables vehicle designers to integrate hydrogen technologies into future generations of vehicles in a variety of ways, including [17]:

1. Dual-fuel combustion engines – BMW, Ford and other manufacturers have illustrated that redesigned combustion engines can effectively operate on hydrogen fuel with the capability to easily switch to conventional fuels such as petrol/gasoline. For example, the BMW 7 Series (H) allows drivers and communities to benefit from the zero-emission behaviour of hydrogen vehicles in dense urban areas where hydrogen refuelling is possible, while also enabling the vehicle to travel beyond H_2 refuelling facilities by switching to an alternative (conventional) fuel at the push of a button. Improvements in the overall efficiency of vehicle drive-trains, or the use of combustion engine-electric drive systems provide further opportunities to enhance energy efficiency [18-20].
2. Hydrogen-enriched fuel streams – conventional combustion fuels can be enriched with 'clean' hydrogen and used in conventional engines to produce overall reductions in the pollution emissions of vehicles without major disruptions to the conventional design. This method also allows limited volume sources of hydrogen to be used in a large vehicle fleet [20, 21].
3. Electric-drive fuel cell vehicles – many vehicle manufacturers have produced demonstration fuel cell (FC) vehicles that utilise the high electric efficiency of

FCs to power small commuter vehicles that are designed to be lightweight and emission free. The integration of innovative technologies such as the regenerative braking found in the Toyota Prius with fuel cells and electric drive systems provides further opportunities to maximise the energy efficiency of future vehicle fleets [22, 23].

4. Auxiliary or boost power systems – hydrogen-based power systems, such as fuel cells, can also play valid roles in meeting the auxiliary power demands of vehicle systems or to assist smaller conventional power plants in meeting peak power demands. Examples of auxiliary power systems include the use of a small fuel cell in the BMW 7H to run the climate control systems (air conditioning) while the vehicle is parked, or to power the refrigeration units in delivery trucks as an alternative to running the diesel engine. Fuel cells can also act as a peak power source, or turbo, for diesel electric long-distance vehicles, reducing the size and weight of the conventional diesel engine while providing a smaller power plant to run auxiliary systems [24, 25].

Hydrogen energy technologies provide considerable opportunities for innovative energy system designs – for vehicles or stationary power applications. Examples of how conventional designs are being reborn through the integration of hydrogen technologies include the futuristic General Motors 'AUTOnomy' concept car or 'skateboard', which is highly dependent on hydrogen and fuel cell technologies [26]. However, the integration of hydrogen energy technologies into conventional society need not be so radical or long-term – opportunities do exist today for hydrogen energy technologies to serve as energy supply systems that reduce environmental emissions, enhance quality of life, and improve the sustainability of our actions.

A European Commission report (2003) on 'trends in vehicle and fuel technologies, review of past trends' looks at the trends in automotive energy systems and the emergence of hydrogen as a viable fuel in conventional and innovative power plants. The report also comments on the failure of other non-fossil energy carriers, such as batteries, to provide viable solutions to powering vehicles and subsequently highlights the need for solutions such as hydrogen energy for transport systems [27].

Christidis *et al.*'s report [27] is extended in the form of a European Union report on "H2 in transport", which describes a best-case scenario for hydrogen and fuel cells in transport and outlines the potential technical, economic and environmental benefits in the long term [28]. Altmann *et al.*'s report provides a comprehensive review of the current state of development of hydrogen technologies and their viability in the transport market place. The study also identifies the main obstacles and boundary conditions for a wide-scale introduction into Europe. The five main issues that were identified as critical for the introduction of hydrogen in transport include:

1. "The cost of fuel cell vehicles and the cost of hydrogen as a fuel are expected to continue to fall in the future as a result of the constant improvement of technologies. A crucial condition for the reduction of costs is the realization of economies of scale in both vehicle and fuel production and the achievement of the perhaps overly optimistic goals of 50-100 \$/kWh. The relative cost of hydrogen compared to conventional or other fuels is the main factor from the economic point of view. The boundary conditions for which hydrogen would have an advantage correspond to the case of high oil prices combined with either low natural gas prices or low electricity prices.

2. The performance of fuel cell or hydrogen-based vehicles can potentially match that of conventional technologies. Fuel cells even offer some advantages in auxiliary power units and some niche markets. But -everything else being equal- hydrogen based technologies do not still offer enough advantages to shift user choices. It is obvious that in order to be competitive, they have to provide comparable performance at comparable cost, with accessible and reliable infrastructure. Otherwise, only a strong shift in user choices towards clean technologies would justify the substitution of the proven conventional technologies.
3. Distribution and storage raise important challenges. The development of a wide network of refueling stations is a major requisite, but would need a critical mass of demand before it takes off. In this context, it is indispensable that the cost of hydrogen distribution is kept low and that its introduction is massive, so that the investment costs are justified.
4. Significant environmental benefits may occur, depending on the primary energy used for hydrogen production. Electrolysis-based solutions would only be beneficial for the environment as long as the electricity used for the electrolysis is produced from carbon-free fuels. Solutions based on reformation of fossil fuels would be neutral from the environmental point of view.
5. The introduction of hydrogen in transport would therefore be feasible only in the case of low cost of renewables in electricity generation or in the case of high-performance fuel cells with low prices of natural gas or biofuels. The commitment of the industry could be influenced by policy. The key industrial stakeholders (car manufacturers, refineries and fuel providers, infrastructure providers, fleet managers) will invest in a new technology only if the future market prospects are clear. The role of policy makers should therefore be that of decreasing uncertainty through suitable and timely policy measures, legislation and standards. Legislation could also influence user choices, by promoting the use of hydrogen, penalizing CO2 emissions, or by limiting the use of conventional technologies in certain areas."

The Altmann *et al.* [28] study also examines the timing by which hydrogen or fuel cells may make a wide scale introduction into the transport sector, expressing the view that 2020 is too early, and questioning whether the year 2030 is a feasible time horizon. The report includes the warning that even if the goal for hydrogen adoption is shifted to beyond 2030, the preparation needs to start now due to effort and degree of change that will be required.

A problem that commonly arises during analysis of hydrogen use in the transport sector is that of securing investments in infrastructure to refuel vehicles before the vehicle market exists, and/or investing in vehicle development when no refueling infrastructure exists. This "chicken and egg" problem is seen by many as a substantial stumbling block to the hydrogen economy due to the significant financial investments required for both vehicle and infrastructure development [29]. Cho predicts that the use of hydrogen-fuelled internal combustion engines (ICEs) will solve the chicken and egg problem, and provide a hydrogen introduction route that circumvents the issues that are faced in the short-term by fuel cells (cost, ruggedness etc) [18]. Service examines these fuel cell related issues in greater detail [30].

The concept of using ICEs as a transition step to developing a hydrogen economy has considerable merit as it enables the use of existing expertise, servicing infrastructure and a relatively low-cost energy conversion device. This provides a faster route for the market development of hydrogen vehicles, subsequently making the development of refueling infrastructure more valid. In essence, a challenging technology leap from fossil-fuelled ICEs to hydrogen-fuelled FCs has been separated into two easier steps of (1) replacing fossil fuels with hydrogen in ICEs, then (2) replacing the hydrogen-fuelled ICEs with FCs. The continued development of fuel cells will enable their gradual introduction into future vehicle fleets, with the necessary refueling infrastructure already available. Continuing the transition strategy fully to the adoption of FCs is important due to the energy efficiency benefits that they offer. Steinberger-Wilkens review of FCs looks at using the 'softer' advantages of FCs as a way of entering the transport market without simply replacing current solutions [31]. The BMW 7H series car demonstrates the potential merits of using fuel cells in auxiliary power systems.

3.3.2 Stationary applications for hydrogen energy technologies

Stationary energy demands, as with the transport sector, are a significant component of global energy use. Although stationary energy use is not as dependent on oil reserves as the transport sector, a very high proportion is sourced from fossil or non-renewable reserves. Conventional energy systems, including those which utilise renewable energy technologies for primary energy generation, have also failed to provide adequate energy services to a large proportion of the global population.

There are many potential applications for hydrogen energy technologies in the stationary energy sector, most focusing on the storage of primary energy sources. Applications can vary in size and role - from meeting or assisting to meet the energy needs of houses and businesses, to providing storage and network stabilization functions for the energy system of a whole country (e.g. Iceland) [32].

Common examples of the roles that hydrogen energy systems and sub-systems (production, storage, conversion) can play in stationary applications include:

1. emergency power systems (replacing, for example, diesel generator sets)
2. storage of off-peak power for peak load shedding
3. storage of excess renewable energy resources
4. the integration of these applications into distributed systems, with hydrogen technologies serving as emergency power systems and to store excess energy in a distributed system.

Hydrogen energy systems, in partnership with renewable energy technologies, are very attractive to some industries as uninterruptible power supplies (UPS) where the cost of energy service failure can be high (e.g. finance, communications etc). The relative cost of not having energy can make even the high cost of hydrogen technologies attractive in these applications (compared to conventional energy systems that are cheaper but not up to the task) [33, 34].

The potential capabilities of hydrogen energy technologies are also very attractive for stationary energy applications in remote and/or off-grid applications where the cost of transporting conventional fuel reserves can have a significant impact on the final cost of energy. This is especially relevant in circumstances where conventional energy systems have proven unsatisfactory for economic, environmental or operational reasons. Examples include:

1. hydrogen technologies used as an energy storage mechanism to compensate for the intermittent nature of local renewable energy resources.
2. hydrogen technologies enabling the utilization of existing commercial renewable energy generation technologies (wind, PV etc) and enhancing the performance of systems, replacing or functioning in partnership with conventional energy storage solutions (batteries, flywheels, etc).

Glockner's work on the HSAPS report (Hydrogen for Stand Alone Power Systems) provides a comprehensive overview of the market potential for hydrogen energy technologies in remote applications [34, 35]. Innovative hydrogen energy systems on Utsira island in Norway and the Shetland Islands in Scotland are demonstrating the success of such systems [36, 37] and the potential to expand the use of stationary hydrogen infrastructure to support local vehicle fleets operating on hydrogen [37].

These projects also illustrate that, as with the use of hydrogen technologies in the transport sectors, technology adoption strategies can be based on the initial use of internal combustion engines (modified to operate on hydrogen 'fuel') while awaiting the commercialization of cheaper and better performing fuel cells.

The Vest Norden (West Nordic) Project, funded by the Nordic Council's 'Nordic Energy Research' agency, examines many of the other issues surrounding the use of renewable and hydrogen energy systems by remote communities in addition to technical challenges. It concludes that the communities considered in the remote Nordic regions (Faroe Islands, Greenland and Iceland) (1) first need to develop efficient energy systems; (2) energy costs from hydrogen systems are not yet competitive; and (3) the great need for support infrastructure (the stationary equivalent of the transport "chicken and egg" problem) will retard the ability of communities to access such technologies [38, 39].

Communities at the other global geographic extreme (Antarctica) also have a history (although relatively short) of considering the use of hydrogen as an energy carrier in their stationary energy systems [40, 41][42]. These applications are comprehensively examined in this thesis.

3.3.3 Mobile devices

In contrast to the anticipated slow market development in the transport sector, hydrogen may be utilised in a number of stationary applications in the near term, particularly in areas where the relatively high costs of hydrogen technologies can be justified. The total number of systems deployed, however, is also expected to remain relatively low in the short term due to the small size of the market and relatively high cost of hydrogen energy systems.

The use of hydrogen technologies in mobile devices presents a potentially substantial market in the near term, where the myriad of electrical devices now prevalent in society could be powered using hydrogen energy in some form [43, 44]. Examples of likely systems include fuel cells running off packaged methanol, providing electricity on-demand for small devices [45, 46]. Alternatively, closed-system hydrogen storage mechanisms can replace conventional batteries as power systems, with recharging from stationary power systems [46, 47]. Recent achievements in improving the efficiency and power output of 'miniature' fuel cells further enhances the viability of replacing conventional and inadequately performing batteries with hydrogen systems in future generations of mobile devices [48]. When these improved fuel cells are coupled with developments in hydrogen storage systems for mobile devices, significantly higher power output and longer lasting energy supply systems for mobile devices will be possible. An example of possible storage improvements that are highly relevant for mobile applications is a water-borohydride solution that can hold one-third more hydrogen than the same volume of liquid hydrogen [49].

Heinzel *et al.* and Dyer discuss the attractiveness of membrane fuel cells as alternatives to conventional batteries over a wide range of power and energy capacity [43, 50]. The main advantages are cited as: (1) the flexibility with respect to power and capacity achievable with different devices for energy conversion and energy storage; (2) the long lifetime and long service life; (3) the good ecological balance; and (4) very low self-discharge. Heinzel *et al.* propose that the fuel for a membrane fuel cell might be hydrogen from a hydride storage system or methanol/water as a liquid alternative. The main differences between the two systems are cited as: (1) the much higher power density for hydrogen fuel cells; (2) the higher energy density per weight for the liquid fuel; and (3) safety aspects and infrastructure for fuel supply for hydride materials. Different system designs are proposed to be better suited for specific mobile applications. High power cells are required for portable computers, low power methanol fuel cells required for mobile phones in hybrid systems with batteries and micro-fuel cells are required for hand held PCs in the sub-Watt range.

The appeal and viability of the mobile device sector as an early market for hydrogen energy technologies can be summarized as: (1) significantly less support infrastructure demands than other sectors; (2) the growing market for mobile devices and also increasing demand for energy supplies that conventional batteries cannot meet [51]; (3) small-scale power demands; (4) low cost products enables higher volumes of sales; and (5) the mobile device market place is traditionally a site for the early adoption of novel technologies.

The viability and appeal of using hydrogen technologies in mobile devices has been assessed as potentially providing an opportunity for "developing countries to leap over the developed world to energy independence". Vogel cites the example of cell (mobile) phones having made land lines obsolete before they were installed in a number of developing countries. With analogous market advantages, hydrogen technologies could gain rapid market penetration in the developing world even (or particularly) where conventional energy supply services are not available [52].

3.4 Advantages of and challenges for the hydrogen economy

As summarised in Table 3.1, the concept of a hydrogen economy offers many attractive features to energy users, such as the ability to store intermittent primary energy sources and to convert any form of primary energy into a useful and versatile vehicle fuel. In addition, the energy carrier or fuel is 'friendly' to the environment and human health. Whilst these characteristics increase the attraction of hydrogen energy technologies relative to conventional energy systems, achieving a transition to hydrogen from fossil fuels for local or global energy systems is an immense task that will present many diverse challenges (see Table 3.2). Specific technical challenges are present within each of the different technology areas associated with hydrogen energy and a wide range of non-technical challenges also exist for local and global efforts to drive the uptake of hydrogen energy systems. These challenges exist in and influence all aspects of human society, such as politics, social welfare, change management, policy and standards, economics, and the environment.

Summary of perceived advantages of the 'hydrogen economy'
1. Enables the development of versatile and flexible energy systems that can use a range of conventional and emerging energy technologies.
2. Enables the use of a wide range of primary energy sources and source materials from a wide range of locations and environments, for the production of a globally common energy carrier.
3. Can be coupled with conventional fossil fuel primary energy sources to enable emission-free fuel for vehicles. Although emissions are still associated with the primary energy production, these could potentially be captured and stored (sequestered) at a central location and the combined system would reduce the amount of emissions and number of emission sources in dense urban areas.
4. Can increase the use of renewable primary energy resources by providing energy storage mechanisms to combat intermittent supply, and providing mechanism to generate vehicle fuels from renewable energy.
5. Potential to support a range of innovative energy system designs, such as decentralised power in stationary systems or auxiliary systems in vehicles.
6. Inherently more efficient energy conversion technologies (fuel cells), providing a mechanism to improve the net efficiency of energy use.
7. Suitable for the development of gradual transition strategies that utilise conventional technologies and energy sources to reach a long-term goal of renewable and sustainable energy systems using a common hydrogen fuel.
8. Enable the development of innovative energy systems that can deliver performance beyond that capable of conventional energy systems (e.g. greater energy density of hydrogen fuel cell systems, or service to communities in developing nations who presently do not have access to modern energy services).
9. Enable the development of independent and clean energy systems for deployment to communities in remote locations or sites of environmental significance.
10. Ultimately enable the development of secure, flexible, sustainable, and accessible energy systems based on the use of local renewable energy resources via the use of hydrogen as a globally common energy storage mechanism and alternative vehicle fuel.

Table 3. 1: summary of advantages of the hydrogen economy relative to conventional energy systems.

Summary of challenges faced by the 'hydrogen economy'
1. Many technical challenges exist within each of the three technology categories associated with the hydrogen economy (production, storage and conversion), representing a very substantial collective challenge to commercial development. 2. Current costs for energy supply from hydrogen systems are too high in comparison to conventional solutions. 3. Development of support infrastructure – ranging from vehicle refueling stations to maintenance and servicing facilities for hydrogen systems. 4. Limited understanding and support within user communities 5. Additional benefits of sustainable hydrogen systems are not valued within conventional economic systems 6. Absence of policies and standards to facilitate the introduction of hydrogen technologies into conventional society 7. Need development of practical experience with laboratory-proven systems to enable further product development and refinement

Table 3. 2: Summary of challenges faced by the 'hydrogen economy'.

Expert opinions remain divided about which challenges are the most significant, how the challenges should be overcome, how long it will take to achieve success, how much it will cost, and even what the challenges are. However, many people agree with the concepts that action is required to address energy issues, hydrogen may play a key role in future energy systems, and that a multifaceted approach will be needed for the challenges facing the development of hydrogen energy systems.

Service, for example, comments that "economic and political difficulties abound, but the most glaring barriers are technical ... at the top of the list: finding a simple and cheap way to produce hydrogen". A significant demand for major infrastructure investment to achieve sufficiently high levels of availability for consumers is also projected, reinforcing the 'chicken and egg' issue of infrastructure/market development (US$500 billion in U.S. for example) [30]. This claim is stoutly refuted by Lovins, who suggests a range of measures to cost-effectively deploy infrastructure and argues that hydrogen markets can be cost-competitive if pursued sensibly [53].

Steinberger-Wilckens, as part of a review of technological change and usefulness with other products/technologies, warns of the challenge of the 'sailing ship effect' applying to hydrogen technologies such as fuel cells. With this effect, incumbent technologies become more competitive in the face of new threats and break away from the traditional S-curve of development. For example, in order to attain significance for the hydrogen technology market, fuel cells will need to meet the cost margins that dominate propulsion, power generation and electricity supply. Suggested actions include identifying niche markets, with low number sales and government supported market introduction schemes; gathering field market experience, and development of better production methods. Projections of the time period 2010 to 2020 are suggested. Steinberger-Wilckens recommends the identification of the 'soft' elements of added value (i.e. not economic) that would drive the uptake of hydrogen technologies such as fuel cells – "product features that offer performance unobtainable with conventional equipment will spur the market introduction of a new product considerably". The paper cites an example of mobile phones, where call costs can be up to 10 times that of fixed line communication, but convenience and other soft features justify the cost to consumers [31].

An Australian Agency for International Development (AusAid) discussion on "power for the people: renewable energy in developing countries" [54] reviewed the constraints to the mainstream adoption of renewable energy technologies in communities. These observations can be applied to the use of hydrogen technologies with renewable energy (RE) technologies in remote communities. Some of the major problems with past RE projects were cited to include: (1) wrong focus; (2) lack of applicability; (3) failure to meet needs; and (4) technical problems.

The United Nation Environment Programme's (UNEP) report, "A simplified guide to the IPCC's "Climate Change 2001: Mitigation"" provides a comprehensive overview of the Intergovernmental Panel on Climate Change's 3rd Assessment Report, analyzing actions to address global climate change through the limiting of greenhouse gas emissions including technologies. The guide identifies barriers to the diffusion of climate-friendly technologies that are also relevant to the deployment of hydrogen technologies. The barriers include (1) institutional barriers exist to some degree in all countries; (2) cultural barriers include current lifestyles, behaviours and consumption patterns; (3) economic barriers send unhelpful signals to producers and consumers; (4) technological barriers can exist in the early stages of a technology's diffusion. The guide concludes that great advances have been made in understanding climate change and mitigation opportunities, and research must continue on resolving remaining uncertainties; and the IPCC findings demonstrate the importance of starting to reduce emissions now (and to long-term strategies to address the barriers that environmentally friendly technologies face).

Numerous studies have been completed on social acceptance and change management practices relating to hydrogen use in communities, particularly in association with demonstration projects [55, 56]. The EU's "Hydrogen in transport" report comments that two central conclusions may be drawn from the eight studies that had been undertaken to date on hydrogen acceptance and social implications: "hydrogen acceptance is generally high, and as soon as people experience hydrogen technology in every-day life they accept and use it" [28]. This is supported by more recent results from the Icelandic bus demonstration project [57]. However, contrasting experiences with other projects such as the H_2 bus trial in Perth, Western Australia, illustrate that hydrogen resistance can be strong in a community and result in considerable damage to projects [58].

From a broader perspective, energy system users may not be ready for innovative energy technologies such as hydrogen from a technological or social perspective. Ulleberg and Rinnans' analysis of the West Nordic project is one example of this situation, where the communities considered were advised to focus on improving the efficiency of their energy systems before considering the introduction of additional and innovative energy generation infrastructure [39].

Concerns and debate about the potential environmental impacts of a wide spread switch to a hydrogen economy have also been raised in a number of fora. Tromp *et al.*'s paper examining the potential (and worst case) impacts of hydrogen fuel leaks on the atmosphere from a global hydrogen economy is a high profile example [59] that stimulated considerable debate and dissent [60, 61].

3.5 *Strategies to drive the development of the hydrogen economy*

Hydrogen technologies are critical for efforts to enable sustainable development [1] and have a wide variety of potential applications in all energy use sectors. The technologies have been proven to work, but challenges to the further development of the hydrogen economy (as summarized in Table 3.2) must still be addressed.

Detailed analysis of the drivers, barriers, actions/measures and overall strategies that relate to the transition to a hydrogen economy have been developed for a wide range of applications, including industries, national energy policies, international partnerships, and for individual user communities. Examples include national strategies and studies for the United States (hydrogen technology roadmap) [62], Australia (National Hydrogen Study) [63], and Iceland [64], Nordic (hydrogen energy roadmap) [65] and European [66] regional studies, international partnerships (International Partnership for the Hydrogen Economy – IPHE) [67]; and industry and sector studies (transport) [68]. A wide variety of literature is also available that reviews approaches to the generation of and recommended contents for hydrogen energy strategies.

Steinberger-Wilckens (SW), for example, reviews technological change and the usefulness of a range of new technologies and relates the lessons learnt from these technologies to hydrogen energy [31]. The technologies reviews cover mineral oil products, mobile phones, photovoltaic panels, green electricity, unleaded petrol, and double glazing and include examples of the market entry of these 'novel' products, their value to the consumer, ecological performance, and overall performance and success. SW hypothesizes that the consumer or end user 'added value' of a product plays a decisive role in the monetary value assigned to a product. This value, defined as a 'desirability', is said to not directly relate to the material value or to the technical performance of the commodity. Therefore, products that are more expensive will be accepted if their added 'soft value' is deemed acceptable for the higher cost. Products offering 'flexibility', 'independence' (in what ever sense) and 'prestige' often have performed best in the way of market conquest, in the absence of policy regulation. However, products with a positive image in public opinion may not be successful if there are doubts on the validity of the image. This analysis is applied to specifically to fuel cell technologies, including how user choices (what is most important) relative to product properties influence the uptake of new products. This leads to a suggestion for fuel cell market strategies to focus on softer values (prestige, usefulness, environment) rather than costs for early markets.

Steinberger-Wilckens calls for the urgent development of a fuel cell market to (1) sell equipment into real world applications; (2) earn revenue; (3) gather experience from real world applications, and thus (4) bring fuel cell technology forward by a decisive step [31]. Only when this has been achieved can mass market entry be considered and tested. SW suggests that a market is already evident for several applications, and the challenge has shifted to supplying functional equipment at realistic prices, including off-grid electricity supply and recreational vehicles.

Barreto *et al.* provide a long-term hydrogen-based scenario of the global energy system, described in qualitative and quantitative terms, illustrating the key role of hydrogen in a long-term transition towards a clean and sustainable energy future

[69]. The paper identifies a need for market strategies that stimulate the coordination of different market segments, such as niche markets. The authors propose a number of markets where factors such as convenience, reliability, and environmental performance could make hydrogen technologies attractive – echoing the sentiments of Steinberger-Wilckens. They suggest that dynamic growth in such niche markets would justify the deployment of large-scale production and transportation facilities later on, when demand increases and become geographically more dense.

Crabtree *et al.*'s general review of strategic development of a hydrogen economy. suggests that early government investment in establishing goals, providing research support, and sharing risk are necessary to prime the emergence of a vibrant, market-driven hydrogen economy [4].

Di Mario *et al.*'s analysis of the socio-economic aspects of hydrogen energy use in the European Union advise that the transition "will require high financial resources, being, ultimately, almost purely capital-intensive" [70]. Their analysis indicates that, apart from the necessary research and technology development (RTD) effort targeting this long-term objective, "appropriate financial mechanisms have to be put in place to facilitate the energy transition towards a fossil-fuel-free system."

Rogner recommends the use of niche applications for hydrogen technologies to stimulate the creation of viable commercial markets in the near term: "On their bumpy road to commercialization, hydrogen production, delivery and conversion technologies not only require dedicated research, development and demonstration efforts but also protected niche markets and early adopters". This recommendation is based on the value of the unique technological properties of hydrogen, and the demonstrated willingness of niche markets to pay a premium for the energy services that hydrogen technologies can offer [71].

Melaina advises that "very high numbers (17,000) of refuelling stations" will be required to achieve a high level of penetration of hydrogen technologies in conventional societies such as large regions of the United States population (e.g. California). Smaller communities such as Iceland or Tasmania, or Antarctica, can enjoy relatively high penetration of serve to the community with much less infrastructure. Therefore, the relative penetration or impact of the next technology in the short-term is much higher, and the issues associated with high penetration of hydrogen in a community can be studied before major infrastructure investments are made in conventional cities [29].

The Baykara review of the role of hydrogen technologies in enabling sustainable development proposes that critical issues relating to use of hydrogen are slowness of market diffusion and slow level of public awareness and subsequent acceptance [1]. Baykara recommends that commercial-scale production and cost-competitiveness of hydrogen technologies could be achieved by highlighting the critical aspects of these technologies, and to allocate resources to problem areas. Following these steps, encouragement of venture capitalism, niche markets, and "early adopter population" would be easier to realise as well. The author then suggests efforts to initiate discussion of these ideas to raise awareness and support. This study seeks to do this in an Antarctic context). The review concludes that hydrogen technologies are "quite mature and ready for implementation", but are at a critical state where they have stagnated at the point of market diffusion because of their high cost and low production volumes (leading to high costs). The cycle can be broken by governmental and international subsidies to encourage initial market pull.

3.6 Progress with the hydrogen economy

Although hydrogen energy systems, as expressed by the International Energy Agency, "still face a number of technical and economic barriers that must first be overcome for hydrogen to become a competitive energy carrier" [72], much progress has been made in the development of the technologies and techniques needed. A wide range of efforts underway are also underway to ensure that this progress continues. They range from investment in technology research and development, to product commercialization, skills development and education programs, international research or political collaborations, industry and government partnerships and a wide range of demonstration projects with local, national and global visions. Relevant examples of these efforts are reviewed below, presented in chronological order.

Veziroglu, 2000, reviewed progress in the first quarter century of the "Hydrogen Energy Movement", commenting that "over the past 25 years, there have been accomplishments on every front - from the acceptance of the concept as an answer to energy and environment related global problems - to research, development and commercialization" [73].

Momirlan and Veziroglu, 2002, followed up on this with a review of hydrogen technology, economics, environmental impacts, special system applications, and hydrogen energy status around the world at the end of the 20th century as well as hydrogen organizations, associations, projects, periodicals and conferences [74].

Elam *et al.*, 2003, provided a comprehensive overview of international research efforts under the auspices of the International Energy Agency's (IEA) Hydrogen Program to collaborate and address the important barriers that impede hydrogen's worldwide acceptance. Through well-structured, collaborative projects, experts from around the world addressed many of the technical challenges and long-term research needs that face the hydrogen community [72].

Sperling and Ogden, 2004, provided a brief but comprehensive review of contemporary issues facing the development of a global hydrogen economy, including drivers, barriers, and opportunities for success [75].

Altmann *et al.*, 2004, in their analysis of the potential for hydrogen as a fuel for transport in the long-term (2020-2030), also reviewed European hydrogen activities and noted the growing importance of and commitment to the field. "Since many years, the EU has been supporting hydrogen & fuel cell research, and there is now a growing importance of this field, as reflected by the substantial increase in financial support. In November 2003 the European Commission Initiative for Growth included a "Quick Start Programme" of projects of public and private investment in infrastructure, networks and knowledge. This programme foresees a major ten year initiative for hydrogen-related research, production and use, with an indicative total budget of €2.8 billion of public and private funding. In addition, the European

Commission launched the European Hydrogen and Fuel Cell Technology Partnership in January 2004" [28].

Crabtree *et al.*, 2004, reviewed the principles and progress of the hydrogen economy. The authors asserted that there are basic technical means to achieve each of the three functional steps of the hydrogen economy (production, storage and use), but none of them can compete yet with fossil fuels in cost, performance or reliability [4]. The authors also proposed that historical precedents suggest that the hydrogen economy should succeed, even with the barriers it currently faces, citing previous examples of new energy sources and carriers flourishing when coupled with new energy converters. They argued that this success will be based on the ability of hydrogen and its own natural energy conversion partner, the fuel cell, to interface intimately with the broad base of electrical technology already in place, and potential to expand to propel vehicles, personal devices, and generate neighbourhood heat and light.

Midilli *et al.*, 2005, reviewed hydrogen energy as a clean energy carrier, discussed the key role of hydrogen energy technologies and systems, and compared hydrogen with other energy forms. Energy strategies that incorporate hydrogen were considered, and the importance of hydrogen energy in achieving a sustainable energy system was discussed. Exergetic, environmental, sustainability and other perspectives were also considered [3].

Fernandes *et al.*, 2005 reviewed the progress of hydrogen technologies in Europe, with an overview of the EU "HySociety" program and European hydrogen projects. The authors commented that although clear progress has been made, "there are several non-technical barriers which must be overcome or removed before hydrogen can be applied in energy systems" [76].

Solomon and Banerjee, 2006, surveyed the global status of hydrogen energy research and development (R&D) and public policy, along with the likely energy mix for making it. The current state of hydrogen energy R&D among auto, energy and fuel-cell companies is also briefly reviewed [19]. Their paper concludes that serious questions about the sustainability of a hydrogen economy can be raised based on the degree of progress with current research and commercialisation programs and suggest that a lack of focus may be one cause for poorer than expected progress.

Penner, 2006, reviewed the general principles and current technologies of a hydrogen economy and examined the present costs of hydrogen production by any of these means. Penner predicted that the hydrogen economy favoured by people searching for a non-polluting gaseous or liquid energy carrier will not be developed without new discoveries or innovations. Conclusions included that hydrogen may become an important market entry in a world where electricity generation provides high-temperature waste heat that can be used to dissociate water in chemical cycles (i.e. in nuclear fission or breeder reactors). Market entry could also be achieved if new inventions and innovations lead to low-cost hydrogen production by applying as yet uneconomical renewable solar techniques that are suitable for large-scale production such as direct water photolysis or low-cost electricity supplies (e.g. generated on ocean-based platforms using temperature differences in the tropical seas) [12].

Examples of more detailed analysis of specific sectors of hydrogen technology research and development can be found with Turner, 2004, who reviews sustainable hydrogen production routes [77]; Conte *et al.*, 2004, (state of the art of hydrogen storage technologies and the prospects for nanomaterials) [47]; and Cropper *et al.*, 2004, or Laramie and Dicks, 2003, with fuel cell technologies [15, 78].

In addition to technology and general 'hydrogen economy' issues, more specific research has been undertaken into socio-economic considerations and the development of specific niche markets – building on the strategy concepts presented earlier. For example, Zoulias *et al.*, 2006, capitalising on the original efforts of Glockner, 2004, applied a techno-economic approach to assessing the market potential of hydrogen energy technologies in stand-alone or remote area power systems [34, 35]. Di Mario *et al.*, 2003 evaluated the socio-economic aspects of hydrogen energy in the European Union. Their analysis indicated that "it is advisable to takc the necessary steps to facilitate the transition towards a renewable/hydrogen system, i.e. the "hydrogen economy" [70].

3.7 Future Directions for Hydrogen Energy

A wide range of activities are being undertaken, under the guidance of carefully developed strategies, to address the technical and social barriers faced by hydrogen energy technologies and their likely use in the global energy economy.

A common component of many of the strategies is the development of early markets for hydrogen technologies through taxpayer-funded support for niche applications. These 'early-market adopters' are anticipated to stimulate growth of the hydrogen economy concept through the creation of markets for equipment and expertise and subsequent development of skills and experience and the demonstration of systems to inspire public confidence.

Appropriate niche applications for hydrogen energy technologies must therefore be identified. The applications with the greatest appeal would provide a reasonable sized market to stimulate product demand, offer some form of direct value to the government for the investment (e.g. increased performance over conventional systems), and serve as an effective demonstration of the concept to other energy users. Potential specialist markets logically include space applications, telecommunications infrastructure, high value eco-tourism or communities in remote regions, recreational boaters, mobile consumer devices, or government vehicle fleets. Although military markets are frequently cited as potential early market-adopters of new technologies, the restricted nature of their use reduces their appeal as dcmonstration mechanisms.

Other benefits of having early market adopters is the opportunity to evaluate the best pathways for development, and to answer precautionary principle-based questions such as "will hydrogen emissions to the atmosphere create larger problems than they are hoped to solve?" [79]. Highly integrated energy systems would therefore be the most attractive as test systems for hydrogen technologies.

Although all potential early adopter markets are valid and appeal to different market sectors or at different times, remote communities specifically offer a number of advantages as integrated early adopter markets for a range of products, encompassing stationary, transport and mobile applications. Remote communities are attractive as early market adopters for a number of reasons: naturally higher energy costs due to the larger burden of fuel delivery costs, potential for cleaner local environments and high profile impacts from emissions, improved opportunities to measure social development impacts due to smaller community population sizes, and potentially a lack of adequate or competing existing infrastructure.

Existing studies such as for Iceland and the West Nordic region review the potential benefits of remote communities as early adopters, but also show that hydrogen is not currently economically competitive for many applications and social issues restrict the viability of deploying hydrogen technologies to such communities [38].

Some projects, including the wind-hydrogen energy systems developed for the islands of Utsira (Norway) and Unst (Shetland Islands), are compelling demonstrations of the technical viability and benefits of hydrogen technologies for such communities [36, 37]. However, the viability and appropriateness of deploying similar systems to all existing communities in those regions is questionable due to the relatively high cost of these systems.

These projects have also demonstrated that remote communities have their own motivations to consider the use of hydrogen as an energy carrier, particularly when coupled with renewable energy resources, and can pro-actively participate in the generation of hydrogen energy projects. These motivators are primarily to reduce energy supply costs (eliminating transport costs), improve energy supply security, and reduce energy-related local and global environmental impacts. The communities may also be interested in the opportunities for community development, image building, or increased tourism that result from hosting such projects. This mutual interest in utilizing cleaner energy technologies provides opportunities for 'win-win' collaborative projects between communities and government-supported consortiums.

A clear example of a set of remote communities that could serve as candidates for government supported early-uptake of hydrogen energy technologies is the international Antarctic research community. The members of this community have compelling environmental and economic needs for more sustainable energy systems, can deliver value to their governments through the improved performance of their energy systems enabling higher quality science, and can serve as inherently high profile demonstrations of innovative and clean energy technologies.

As with any of the early adopter markets suggested for hydrogen energy technologies, a number of issues must be considered. Can hydrogen technologies play valid and appropriate roles in these operations? How should the technologies be implemented? What strategies are needed? What lessons and outcomes could be transferred to other markets, and how (particularly from Antarctica)? This research will address the questions of 'if' and 'how' the future of the hydrogen energy economy could be influenced by the possible use of hydrogen technologies in Antarctic communities, including if the communities should serve as early adopters of the technologies.

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Chapter 4. Energy & communities in Antarctica

Antarctica is the Earth's most southern and only polar continent - a remote and virtually empty land of pristine wilderness, charismatic wildlife, and harsh weather.

For the past five decades, humanity has had a permanent presence on the continent through a relatively small but international community that has focused on scientific study. Their presence has been critical (and remains so) for a range of scientific disciplines that have contributed knowledge to important and global issues such as long-term climate change or the sustainable management of marine resources.

Although the community of scientists and support personnel living in Antarctica is small in comparison to the populations of other continents, their occupation results in harmful impacts to the fragile Antarctic environment, including the persistent emissions associated with the use of fossil fuels for energy production [1-4]. The community is also responsible for higher than average per-capita contributions to the global environmental impact of fossil fuel use (carbon dioxide emissions etc) [5].

These environmental impacts and a range of other factors provide strong motivations for the international Antarctic community to identify and implement energy supply methods that reduce or eliminate the demand for fossil fuels. As examined in Chapter 3, this search for alternative energy supply methods is shared by energy-using communities around the world. Renewable energy technologies, particularly when used in partnership with conventional energy technologies (hybrid systems) have been proven to be viable alternatives to fossil fuels for remote communities. The "Bushlight programme" for indigenous communities in Australia is a clear example of the successful use of renewable energy technologies in isolated communities (www.bushlight.org.au). The integration of innovative energy carriers such as hydrogen can further enhance their suitability for use in extremely remote Antarctic communities.

This chapter provides an overview of Antarctica and the international Antarctic research community, examining the size and scope of operations, energy demands and methods of supply, and the unique international treaties and legal instruments that influence the operations and energy supply systems in the region. The activities of one leading Antarctic research community/organisation – Australia – are examined in greater detail.

It must be noted that it is quite difficult to get information about the relatively closed world of Antarctic operations – the approach of Antarctic communities towards their activities in the region is generally to 'get the job done'. Few records have been kept in the past, and a negligible amount of information is published in a traditional sense. Most information, therefore, has to be gained via anecdotal evidence and discussions with the people doing the jobs. Much of the following material was gathered through formal and specialist studies on Antarctic operations at the University of Tasmania [6], through paid and collaborative work with the Australian Antarctic community, and discussions with operations personnel from other national Antarctic programs.

4.1 *Antarctica as a physical environment*

Antarctica is a region of extremes – the coldest, driest, windiest, highest, and most remote continent on Earth. The continent is perpetually covered in ice, except for coastal areas (totalling 2% of land area) that are swept clean of ice and snow by gale force katabatic winds (up to hundreds of kilometres per hour) during summer seasons. The ice-covered area doubles in size due to sea ice formation (to approximately twice the size of Australia) each polar winter, making the continent virtually inaccessible. The winter period also sees darkness descend over much of the continent for several months. Summer temperatures are a brisk 0 to -40 °C, with winter temperatures dropping as low as -89.2 °C. The continent is surrounded by one of the roughest oceans in the world, and is so harsh in climate that only a few living creatures remain there throughout the year. Although devoid of plant life beyond hardy lichen and moss, the continent is rich in resources with 70% of the world's freshwater locked within the deep ice layer covering the continent, and contested predictions have been made of rich seams of minerals in the bedrock below. The surrounding waters (including the shifting ice edge) are very rich in marine life, and the Antarctic region plays a key role in the development of global climate and weather patterns. The location of the Antarctic continent in relation to other land masses is indicated in Figure 4.1, illustrating its remote and polar location.

The fact that this harsh and pristine physical environment has existed for millions of years makes Antarctica attractive to the scientific community as it has preserved substantial information on the physical history of the Earth within the rocks and ice of the continent. Antarctica also provides an optimum terrestrial viewing platform for examination of outer space and the Earth's upper atmosphere. Due to the significant role of the Antarctica continent and the surrounding Southern Ocean in global weather patterns and climate trends, it is also important to study any physical changes in the Antarctic region itself. A number of key facts about Antarctica and a review of the importance of Antarctica in the scientific realm is provided by the Scientific Committee on Antarctic Research [7].

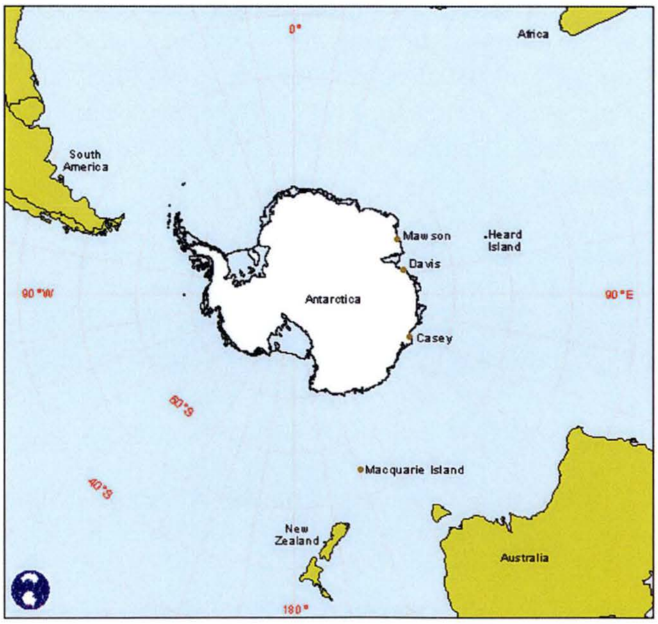

Figure 4.1: Map of Antarctica and the Southern Ocean and surrounding continents [8].

4.2 Overview of the international Antarctic research community

The Antarctic continent has been the subject of human interest for centuries – first as a mythical southern land of paradise, then as a rich source of marine life in the surrounding ocean for whaling and sealers, and as land for exploration and physical conquest. Competing claims for the first human contact with the continent in the 1600 and 1700s have been made by the United States, the former Soviet Union and the United Kingdom. However, the harsh climate and remote location have discouraged settlement by humans and the region has remained virtually untouched since human discovery.

Antarctica now holds a unique place in human history as a land owned by no one nation, and dedicated to peaceful and scientific international collaboration. This situation began with the organisation of an International Geophysical Year (IGY) in 1957-8 [9], involving sixty-seven nations and the use of sixty-five research stations – the first substantial and coordinated effort to research and 'settle' the continent.

Following the IGY, the role of Antarctica as a wilderness reserve and international scientific laboratory was formalised through the entering into force of an international Antarctic Treaty in 1961. The original Treaty membership of twelve nations (Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, United Kingdom, United States and USSR) has since expanded into a broad community of 45 nations (in various member categories) [10].

As a consequence of the framework of collaboration provided by the Treaty, the Antarctic continent is now the focus of a diverse range of scientific research activities that involve thousands of scientists and support personnel from the 45 member nations, and other nations with interests in Antarctica.

This community is composed of scientists from many disciplines, support personnel to enable the conduct of operations, and staff within the fields of administration, policy and government. The community subsequently involves government agencies from the participating nations, local, national and international research institutes, educational institutions, private companies, and non-government organisations.

The Antarctic Treaty has proven to be a unique, very successful, and flexible instrument of international law. Over the past 44 years it has evolved to include a range of instruments that direct the activities and actions of the Antarctic community. For activities that incorporate the energy systems and operations of Antarctic communities, instruments such as the 'Madrid Protocol' that relate to the protection of the pristine Antarctic environment are of particular relevance. These legal instruments and the general operating procedures of the international Antarctic research community and reviewed in greater detail below.

4.3 Antarctic legal instruments and their influence on operations

Following the first Antarctic Treaty Consultative Meeting (ATCM) in 1961, the members have met frequently (now annually) to discuss issues as diverse as scientific cooperation, measures to protect the environment, and operational issues. The Antarctic Treaty has subsequently evolved into a system with a number of components that meet the special needs of managing activities in the Antarctic. This 'Antarctic Treaty System' (ATS) comprises the Treaty itself and a number of related agreements. It also includes a range of organisations that contribute to the work of the decision-making forums. The Treaty Parties have put in place rules relating to specific issues. The development of these agreements has allowed the implementation, with greater precision, of legally-binding provisions for the regulation of activities in Antarctica within each of the member states [10].

Of particular relevance to operational issues and the supply of energy is the 'Madrid Protocol', or Protocol on Environmental Protection to the Antarctic Treaty. The Protocol was adopted in 1991 in response to proposals that the wide range of provisions relating to protection of the Antarctic environment should be harmonised in a comprehensive and legally binding form. It draws on and updates the Agreed Measures as well as subsequent Treaty meeting recommendations relating to protection of the environment. Principles of the Protocol are outlined in Table 4.1. The practical management of Antarctic operations within the framework of the Antarctic Treaty System is examined in the following section.

Environmental principles of the Madrid Protocol

The Protocol provides that protection of the Antarctic environment and dependent and associated ecosystems and the intrinsic value of Antarctica must be fundamental considerations in the planning and conduct of all human activities in Antarctica. With this aim, all such activities are to be planned and conducted so as to [11]:

1. limit adverse impacts on the Antarctic environment; and
2. avoid

a. adverse effects on climate or weather patterns;
b. significant adverse effects on air or water quality;
c. significant changes in the atmospheric, terrestrial (including aquatic), glacial or marine environments;
d. detrimental changes in the distribution, abundance or productivity of species or populations of species of fauna and flora;
e. further jeopardy to endangered or threatened species; or
f. degradation of, or substantial risk to, areas of biological, scientific, historic, aesthetic or wilderness significance; and
g. accord priority to preserving the value of Antarctica for scientific research.

The environmental principles in the Protocol also include requirements for:

1. prior assessment of the environmental impacts of all activities: and
2. regular and effective monitoring to assess predicted impacts and to detect unforeseen impacts.

Table 4.1: Environmental principles of the Madrid Protocol.

4.4 The practical management of the International Antarctic community

Although the Antarctic Treaty System promotes and facilitates a high level of collaboration between the different member states, the practical management of the operations of the international Antarctic community is addressed on a national level. Individual member nations operate individual Antarctic programs of varying sizes, with a range of government goals and research activities. This results in a diverse range of operations between the different parties, and activities are well distributed around the continent. The largest operations include those of the US, UK, Australia, Germany, France. Individual nations may collaborate with other members of the Antarctic treaty who are national neighbours, have neighbouring facilities in Antarctica, or who share common scientific interests.

These individual programs by national operators (member states of the Treaty) interact with one another through the framework established in the Treaty system, principally through the annual Antarctic Treaty Consultative meetings, but also via a number of other committees.

The key decision-making structures within the Antarctic Treaty System include:
1. The Antarctic Treaty Consultative Meeting (ATCM); the high level decisions relating to Antarctic activities and policies are made here; the secretariat for these meetings was recently established in Argentina (2004).
2. The Council of Managers of National Antarctic Programs (COMNAP); primarily involving the operations and engineering personnel of national programs, COMNAP is a bi-annual forum for sharing of information relating to the operations of Antarctic programs. The secretariat for these meetings is based in Australia.
3. Operating below COMNAP are the Standing Committee on Antarctic Logistics and OPerations (SCALOP); and
4. the Committee for Environment Protection (CEP).

A number of science-focused committees have also been established, including:
1. The Standing Committee on Antarctic Research (SCAR);
2. The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

A comprehensive overview of these decision making structures is available from the Australian Antarctic Division web site [12] or sites relating to the committees [13].

In terms of the specific decisions relating to the operations of Antarctic communities,
1. Decisions are made within national programs about the day to day operations;
2. Discussions are made via working groups within the SCALOP framework regarding issues that are common to the international community (eg. energy efficiency working group); and
3. Information is shared between and disseminated to other operations professionals via the bi-annual SCALOP and COMNAP meetings.

For the individual Antarctic programs of ATS member states and the international community as a whole, conducting operations in Antarctica incorporates a number of key activities, including:

1. Development of transport systems to and around the Antarctic continent.
2. Provision of accommodation for scientists and support personnel who are living and working in the region.
3. Communication systems
4. Conducting research activities
5. Energy systems

The five categories of activities are generally undertaken independently by the different nations, although there is an increasing level of collaboration between individual nations to provide access to nations with fewer resources (or no Antarctic research experience) or to increase the efficiency and productivity of operations. Common examples include scientific collaboration for ship-based research programs or the sharing of fuel deliveries by the United States and New Zealand Antarctic programs, which have neighbouring facilities.

The categories of transport systems, accommodation systems and energy systems are the most important with regards to environmental impacts and energy demands for operations, and so are examined in greater detail below.

An overarching structure is provided by COMNAP for the sharing of knowledge and experience in Antarctic operations, and to raise issues of interest to the Antarctic 'operations' community as a whole. The COMNAP web site provides a comprehensive review of the member nations and their programs and operations.

4.4.1 Transport systems

Access to the Antarctic continent is undertaken by ice-strengthened ships or long-range aircraft. Depending on destinations in Antarctica, departure points, and vehicle choices, journey times can range from flights of 6-12 hours, to ship cruises of 3-12 days. Departure points to Antarctic are generally from 'Antarctic gateway cities' located in the Southern Hemisphere, with any journey including a crossing of the hazardous Southern Ocean and landing or mooring in the ice-covered region. Scientific research activities are also conducted by vessels in the Southern Ocean throughout the year, and data is collected from the continent using a range of remote sensing systems, such as space satellite or automated weather stations.

Transport within Antarctica is undertaken on a local, region and intra-continental manner and incorporates a wide variety of vehicles and systems. This includes land vehicles, fixed wing aircraft, helicopters, small boats and large ships.

Antarctic transport systems are responsible for the delivery and distribution of practically all resources associated with a human presence in the region – people, food, equipment, building materials, transport of waste out of the region, and energy (fuel) for the powering of all operations.

4.4.2 Accommodation systems

Once on the continent, Antarctic 'expeditioners' must live in the region for periods of time that can range from days or weeks, to months and years. This has resulted in the development of a range of permanent facilities around the continent and a constantly changing selection of temporary field camps. These accommodation systems range in size from substantial and permanent installations that are capable of housing hundreds of people and include comprehensive suites of supporting infrastructure, to small summer-only field camps that provide only essential services to a handful of expeditioners. In the year 2004 alone, the Antarctic community was involved in the operation of approximately seventy research facilities around the continent [1, 2].

At these permanent and temporary sites, people live and work, consume energy, generate waste, establish their own 'habitats', while seeking to conduct research in an environment that is scientifically attractive because of the previously limited impact of humans.

4.4.3 Energy systems

Antarctic operations are energy intensive – substantial transport distances are associated with the delivery of all goods and equipment to and around the continent; Antarctic research communities undertake complex and highly technological operations with high energy demands; and the cold ambient temperatures require heating for all sites of human occupation.

In general, the energy systems for all activities in Antarctica – essentially transport and stationary power generation - are based on the use of fossil fuels. Ship-based passenger and cargo transport or marine research consumes millions of litres of fuel each year. Each continental research facility consumes fossil fuels for stationary power generation and the transport of personnel, food, equipment and fuel to and around the region. The use of renewable energy technologies for energy generation has emerged over the past two decades for applications on small scale, and recent efforts are examining their use for larger applications.

The evolution of Antarctic energy systems to include increasing usage of renewable energy technologies and alternative energy carriers such as hydrogen is examined in greater detail below, following an analysis of the broad categories of environmental considerations that relate to Antarctic operations.

4.5 *Environmental considerations for Antarctic communities*

The Madrid Protocol dictates strong words in relation to considering the environmental impacts of Antarctic operations. The broad categories and sources of environmental impacts that can result from human activities in Antarctica are listed below, and examined in detail in the following sections:

1. Transport, transfer and storage of fossil fuels.
2. Combustion of fossil fuels for energy production.
3. Location of stations and field camps.
4. Infrastructure footprints.
5. Disposal of waste.
6. Introduction of foreign species.

4.5.1 *Transport, transfer and storage of fossil fuels*

Antarctic operators transport millions of litres of fossil fuels across the Southern Ocean every year, traveling into ice-covered waters to deliver their cargo. This fuel is then transferred to storage tanks on the shore with flat hoses. Fuel is also transferred and stored ashore using smaller drums and tanks. The potential for fuel spills and leaks presents practical limitations during the delivering/transfer stage and for storage. These same challenges emerge when refueling activities are undertaken in field environments, where infrastructure is often temporary.

COMNAP has assessed the risk of fuel spill in Antarctica as one of the most significant threats facing operations based on the likelihood of an 'incident' and the probable impact from the release of fuel into the environment [1].

4.5.2 *Combustion of fossil fuels for energy production*

The consumption of fossil fuels in Antarctica results in emissions such as carbon dioxide and particulate emissions to the local and global environments. These emissions, whilst relatively small in magnitude on a global scale, are very high on a per capita per annum basis when compared to conventional communities around the world (as presented in Table 4.2). Recent studies have indicated that the emissions associated with the use of fossil fuels for energy production are highly persistent in the Antarctic environment and can have severe impacts on indigenous flora, fauna and marine life [1-4].

The use of combustion engines for conversion of fossil fuels to energy, either in stationary energy systems or in vehicles, also results in the release of noise pollution to the surrounding environment. In areas where anthropogenic impacts must be kept to a minimum, such as around breeding wildlife, the sound of a diesel or gasoline generator or vehicle engine can be significant.

	GJ of energy per capita per annum	*Tonnes of CO_2 per capita per annum*
Antarctic shipping	4362.8	310.49
Mawson station	1040.7	72.50
United States	360.6	5.51
Western Europe	159.1	2.12
Qatar	972.2	13.79
Ethiopia	1.1	0.01
Japan	181.7	2.48
China	32.6	0.65
Australia	269.3	5.08

Per capita figures based on population statistics for the station in the relevant year.

Table 4.2: comparison of energy use and emissions for global populations and Antarctic operations [5].

4.5.3 Location of stations and field camps

As the pristine Antarctic environment is challenging for all life forms, the location of permanent and temporary Antarctic research 'bases' becomes an important consideration when the environmental impacts of human activities are considered.

Many of the permanent stations established in Antarctica are located in the coastal areas that are ice-free during summer periods [1, 2]. This provides convenient access for shipping and the ability to build on solid ground (not ice). However, these ice-free areas represent a small proportion of the Antarctic continent (2%) and are also attractive to the indigenous populations of bird and marine life who seek safe areas for breeding and nesting. Consequently human activities near these stations can have a negative and cumulative impact on the local environment and potentially affect local wildlife populations at critical points in the breeding cycles. Temporary field camps can also result in impacts to much broader sections of the Antarctic region. Although not cumulative in nature, the incremental contamination of a growing number of individual sites throughout Antarctica can ultimately lead to an increase in the overall level of environmental impact for the region.

This potential to impact specific sites through direct activities at the site or more diverse activities in the region has been addressed in part through the recent formation of a program to identify and specifically protect Antarctic Specially Protected Areas (ASPAs). Annex V of the Madrid Protocol entered into force in 2002, stipulating that sites designated as being of special interest under pre-existing guidelines were redesignated and renumbered as Antarctic Specially Protected Areas (ASPAs). Building on similar previous mechanisms, ASPAs achieve protection of values within their boundaries by requiring permits for entry and the conduct of activities in accordance with a management plan. The Antarctic Treaty nations have developed guidelines for assessing areas suitable as ASPAs, and for preparing the required management plans, which are submitted by the proposing nation to the Committee for Environment Protection and approved at an Antarctic Treaty Consultative Meeting. To protect discrete areas containing values of outstanding significance, the Antarctic Treaty Parties have declared a number of ASPAs which protect outstanding environmental, scientific, historic, aesthetic or wilderness values, any combination of those values, or ongoing or planned scientific research. It is an offence to enter a protected area without a permit and the permit must not authorise any activity that has not been authorised by the plan of management . Examples of ASPAs include pristine regions that have not changed for millions of years (e.g. the Dry Valleys), or sites of delicate flora and fauna where the normal challenges of daily life are harsh enough without the additional impact of human activities.

4.5.4 Infrastructure Footprints

The total land area occupied by Antarctic facilities – the infrastructure footprint – can also have a significant but passive impact on the local environment due to the competition for solid ground for habitation that emerges between human and 'local' residents. A relatively recent development in the Antarctic Treaty System is the need for human activities to make no permanent impact on the environment, thereby requiring the full removal of any signs of presence when departing from a site. This is driving a change in station design away from those that use substantial concrete structures and foundations.

4.5.5 Disposal of waste

Any human presence results in the generation of waste, such as packaging materials, food refuse, effluent and dirty water from washing and ablutions, or building materials from construction and maintenance programs. In Antarctica, these waste streams are generated at all sites of human occupation and activities, including both permanent stations and field sites.

The methods of handling and relative disposal of this waste can have significant and long term impacts on the Antarctic environment. Historic practices resulted in the careless dumping of all manner of waste into convenient reservoirs such as nearby waterways or ravines [14].

Modern practices include the full tertiary treatment of waste water prior to release in marine areas away from wildlife breeding sites, high-temperature incineration of selected solid waste, and the full removal of waste and recycling materials from the continent (e.g. back to Australia) [15].

Not all Antarctic operators follow these best-practice methods of waste handling – the dumping of untreated waste water streams and poor management of solid waste streams still occurs.

A number of countries operating in Antarctica, including Australia, are investing significant effort to right their past wrongs, such as carefully removing old waste dumps from ravines. These remediation efforts present significant challenges since well-meaning disturbance of decades-old junk often releases more waste into the environment than simply leaving it be. For example, attempts to remove a rusting oil drum from a dump could release the remaining drum contents into the surrounding environment. As all activities have to be undertaken in summer where streams of water from melting ice often course through ravines – where the rubbish has been dumped for decades – the released oil can quickly end up distributed over a wide area and transferred into the local marine environment. Clean-up efforts are subsequently slow, careful, and very expensive [16].

4.5.6 *Introduction of foreign species*

The international community works hard to protect Antarctica's unique biodiversity through stringent quarantine protocols that aim to prevent the introduction of any form of foreign species, whether they be pathogens, grass seeds or animals. Historic procedures were very lax with regards to quarantine and some expeditions actively sought to import foreign species of plants and animals. Conventional practices are now significantly stricter.

Examples of the quarantine-related processes that must be undertaken include high-temperature sterilization of all building materials such as sand and cement. In such cases, supplies cannot be simply loaded from a regular supplier in an Antarctic gateway city such as Hobart, but must be specially processed to remove/kill potential introduced species. Expeditioners travelling to the continent must thoroughly clean all clothing and equipment before arrival, including vacuuming pockets and sterilizing the soles of footwear. Even the delivery and use of foodstuffs is regulated to prevent the delivery of stowaways (such as the humble fly) to Antarctica or the transfer of food-based pathogens to local wildlife. The consumption of chicken, for example, is permitted at Australian stations but banned in field environments due to concerns about the potential transfer of avian viruses to local bird and penguin populations (even though the chicken is fully safe for human consumption) [17]. The use of working animals such as the socially and occupationally valuable 'Husky' dogs in Antarctica is also banned under the foreign species regulations of the Madrid Protocol – a valid use of the protocol but a sad loss to communities in the region.

In regards to Antarctic energy systems, the quarantine restrictions are not likely to have significant impacts but could influence the use of emerging biology-based technologies for the production of electricity or hydrogen fuel in the long-term.

4.6 *The evolution of Antarctic energy systems*

The operations of individual national programs and the international Antarctic community as a whole are currently solidly based on the use of fossil fuels for energy generation. This common dependency on imported, polluting, increasingly expensive and unsustainable energy resources is seemingly at odds with the concept of conducting research in a region that is scientifically attractive because of its pristine and untouched nature.

Ultimately the use of fossil fuels in Antarctica could be seen to be in violation of the principles of the Madrid Protocol, whereby the "protection of the Antarctic environment and dependent and associated ecosystems and the intrinsic value of Antarctica must be fundamental considerations in the planning and conduct of all human activities in Antarctica".

From a historical context, the use of fossil fuels has been a proven, cost-effective and acceptable method of supplying energy for Antarctic operations. No practical and viable alternatives existed during the initial period of establishing operations and communities in Antarctica, and very few motivations have emerged in the following decades to drive Antarctic communities to consider the costs, challenges and risks associated with the use of alternative energy systems.

The entry into force of the Madrid Protocol in 1991 and the emergence of a greater appreciation of the faults of conventional energy technologies, coupled with the development of viable alternative energy technologies in the last few decades, has prompted many Antarctic communities to consider methods of reducing their dependence on fossil fuels for energy production [18].

The motivations of these communities have much in common with those presented for the global energy-using community in Chapter 2 – but are perhaps more extreme and therefore compelling. In comparison to many other 'remote' communities, Antarctic stations and operations have larger fuel delivery distances and their energy costs are subsequently higher; from an environmental perspective they are dealing with a valuable and very clean natural environment so the relative impacts of human activities are greater, and the relatively high energy demand of operations results in greater per capita contributions to CO_2 emissions; the very remote locations and harsh physical environment generate greater risks to energy supply security; and the highly technological nature of many Antarctic research operations demands reliable and high performing energy systems that can support a wide range of activities.

The common ground shared by Antarctic communities and the broader global community of energy-using communities extends to the methods and techniques that have been applied to reducing the use of fossil fuels. These actions have included – as initial steps - the development of more efficient energy systems and programs to change user behaviour to reduce total energy demands within Antarctic communities.

Harnessing the continent's renewable wind and solar energy resources has also proven to be very effective for the clean, reliable and cost-effective generation of power for small-scale applications [19, 20]. Actions such as the installation of a 600-kW wind farm at a coastal Antarctic station (Mawson) in 2003 are providing opportunities to study the roles of renewable energy technologies to provide alternative primary energy sources to fossil fuels for larger operations [21].

The use of nuclear power in Antarctica is prohibited under the Antarctic Treaty System, eliminating it as a potential candidate to replace fossil fuels for applications such as stationary power generation. However, nuclear powered ice-breaking ships are frequently used for transport to the continent by the United States program (and some others). A relatively small nuclear reactor was operated at the United States coastal base of McMurdo from 1962-1972, with an electrical output of approximately 1250 kW. The plant was shut down in September 1972 after wet insulation was observed around the reactor pressure vessel, which was attributed to leakage in the shield coolant piping. A belief that the use of nuclear material for energy production did not contravene the 'no nuclear' components of the Treaty and that reactors could significantly reduce the volume of fossil fuels used on the continent enabled the project to go ahead. The leaking of contaminated materials into the Antarctic environment and subsequent need to remove substantial quantities of contaminated material from Antarctica ended the reactor's short life also curtailed the potential for small-scale nuclear power plants to serve as the dominant energy systems for Antarctic communities. The event ultimately soured all perspectives towards the use of nuclear power in the Antarctic region and no further attempts have been made to deploy reactors. As a consequence, nuclear power is not considered further in this study.

Although the use of renewable energy has shown considerable promise for achieving independence from fossil fuels for Antarctic operations, the intermittent nature of renewable resources creates a critical need for effective methods of energy storage [22]. Successful storage solutions must be capable of supporting the diverse range of operations undertaken by Antarctic communities, including stationary, transport and mobile activities, and integrating well with existing and future infrastructure.

As examined in Chapter 3, hydrogen is rapidly gaining credibility and support as a viable and diverse alternative energy carrier and is potentially well suited for use by remote communities. This potential has been understood for over a decade by a number of members of the international Antarctic community, and for some nations (e.g. Australia), hydrogen forms an important component of long-term plans to achieve independence from fossil fuels .

A more detailed understanding of the operations of Antarctic community and motivations for their use of hydrogen energy can be gained through analysis of a case study – the Australian Antarctic program.

4.7 Case study – Australia's activities in Antarctica

Australia is a leader in the international Antarctic community and its operations are comparative in scale and scope to those of other Antarctic nations. It has established a precedent for proactively pursuing low environmental impact operations and sustainable energy system solutions for its activities. For these reasons it is an appropriate program to serve as a case study of the operations of Antarctic programs and the development of more sustainable energy systems. Australia has also already established an interest in the use of hydrogen as an energy carrier for renewable energy resources, and has actively encouraged specific analysis of the potential use of hydrogen in their operations.

Australia's important and representative position in the international Antarctic community can be further summarized by the following points:

1. Australia has a latent claim to 42% of Antarctic territory, however the claim has been effectively 'frozen', along with the claims of six other nations, since the ratification of the ATS.
2. Australia is original signatory member of the Antarctic Treaty
3. It is a substantial 'player' in the international Antarctic community from the perspective of operational size and scope, financial investment, scientific output, and contributions to the on-going development of the ATS. Australia has also assumed a leadership role in a number of key areas, such as hosting the COMNAP secretariat, holding chairmanship of the COMNAP (2005-6), and leadership of other important scientific committees and organisations.
4. Australia's operational program in Antarctica is extensive, with three permanent coastal stations and regular field expeditions, a significant transport and research shipping program, and a young but evolving intercontinental air transport system.
5. Australia's operational experience in the region is extensive, including initial charting of the region (relating to the sleeping territorial claim), and it claims operation of the oldest permanently operating Antarctic station (Mawson).

6. Australia collaborates extensively with other Antarctic nations for scientific research and operations, and also welcomes the involvement of other non-ATS member nations with interests in Antarctic research (e.g. Malaysia).
7. It has established a leadership position in promotion and implementation of environmental impact-related activities, including the development of comprehensive quarantine procedures and the clean up of contaminated waste sites, and also played a pivotal role in the formation of the Madrid Protocol.
8. In specific relation to energy systems, the Australian program has proactively pursued the testing and implementation of procedures to minimise dependence on or the impacts of fossil fuel use for energy production. This has included the testing of renewable energy technologies of various generation capacities [5].
9. Australia's Antarctic program is based in Hobart, Tasmania – one of the key 'gateway cities' for convenient access to the Antarctic region. A diverse and dynamic community has subsequently developed in Tasmania, focusing on the execution and support of Australia's scientific research activities in Antarctica.

The following sections examine the Australian Antarctic community, their operations, energy systems, and their efforts to move towards more sustainable energy systems that include the use of hydrogen technologies.

4.7.1 Overview of the Australian Antarctic community

The Australian Government Antarctic Division (AAD) leads Australia's Antarctic Program. As an agency of the Department of Environment and Heritage, their charter is "to ensure Australia's Antarctic interests are advanced" [24].

The Australian Antarctic Program has four goals [24]:
1. Maintain the Antarctic Treaty System and enhance Australia's influence in it;
2. Protect the Antarctic environment;
3. Understand the role of Antarctica in the global climate system; and
4. Undertake scientific work of practical, economic and national significance.

These goals are achieved through the activities of the Australian Antarctic research and support communities. The research community is led by the AAD, but involves researchers from Australian and international universities and institutions. The AAD is based in Hobart, Tasmania. The Antarctic support community is also based in Hobart, where a small but dynamic and multi-skilled network provides many of the general or specialist skills and equipment that is needed for Antarctic operations.

From a municipal and cultural context, the city of Hobart has a strong connection with the Antarctic community and continent and brands itself within the international community as a capable and convenient 'gateway city' for the continent. Other national Antarctic programs, such as the French Antarctic program, subsequently use Hobart as a base for supporting their operations in the Southern Hemisphere.

The University of Tasmania in Hobart also serves as the core for Antarctic-related education programs in Australia, with a range of tertiary research and coursework programs offered through the Institute of Antarctic and Southern Ocean Studies (IASOS) [25].

4.7.2 *Overview of Australia's operations in Antarctica*

Australian access to the Antarctic continent has traditionally been achieved through the use of ships – either multipurpose vessels specifically designed for service by the AAD or leased vessels that are suited to specific tasks such as heavy cargo delivery. Anything used in Antarctica must be capable of being loaded and transported to the continent using these vessels – which presents significant challenges in large infrastructure projects. The *RSV Aurora Australis* (AA) is Australia's Antarctic flagship, a multipurpose research and resupply vessel capable of operating in the Southern Ocean (an *ice-strengthened* vessel but not an *ice breaker*), carrying 109 passengers, delivering cargo and fuel, undertaking marine research, and launching helicopters [26]. The AA is the only vessel currently under charter by the AAD.

Travel to Antarctica by ship can take around 10-14 days (without delays for en-route marine science activities) due to the long distances to the continent as (Figure 4.2). Planned delays to complete marine science experiments or visit multiple stations in a single voyage, and unplanned delays such as heavy sea-ice, can significantly extend the amount of time that *expeditioners* spend getting to Antarctica. As replacement for the slow transport by ship, the AAD is developing an innovative air transport system. The air service will link Hobart in Tasmania with Casey station in Antarctica using an Airbus A319 aircraft [27]. Smaller and sturdier planes (CASA C212) and helicopters will fly personnel and equipment between the stations and field camps. The planes will reduce the travel time to approximately 6 hours, but also significantly reduce the amount of cargo and equipment that can be transported with passengers to the region.

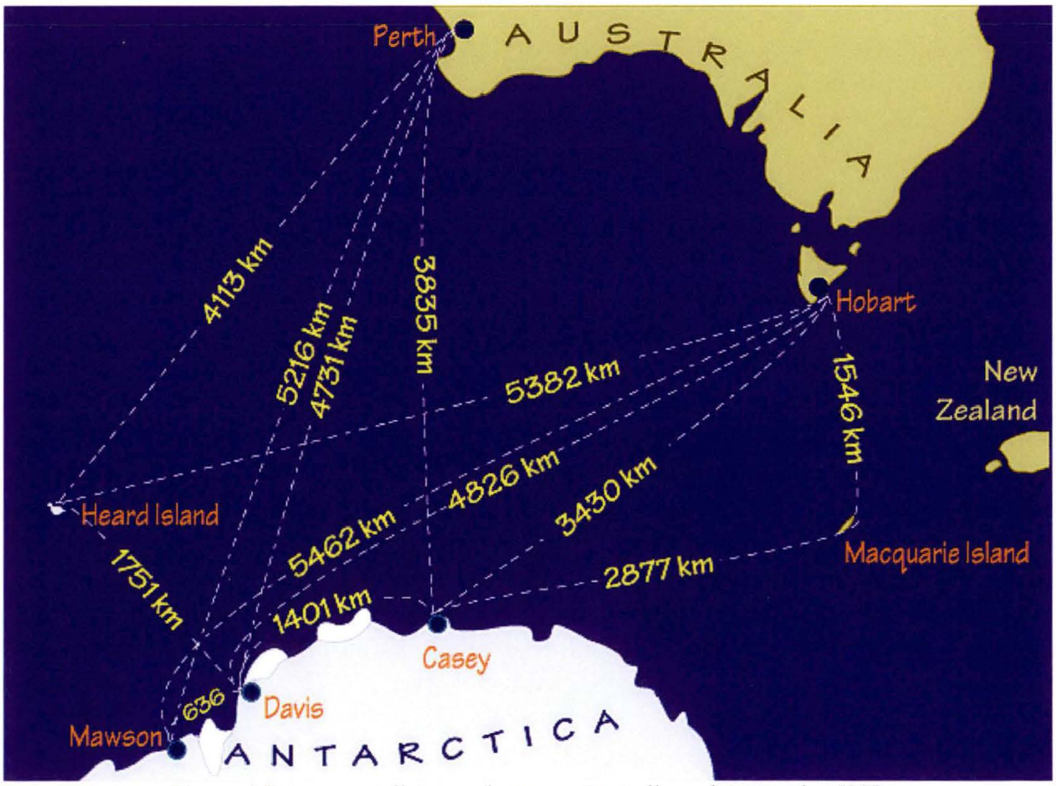

Figure 4.2: transport distances between Australia and Antarctica [28].

4.7.3 Australia's Antarctic energy systems

The energy systems used to support operations in Antarctica are solidly founded on the use of fossil fuels, in alignment with the accepted practices of many remote communities. Fuels such as diesel (Special Antarctic Blend, SAB), liquid petroleum gas (LPG), and aircraft fuels are used extensively for stationary power generation at the permanent stations and field camps, for heating and cooking in small field camps, and to power land, sea and air vehicles. SAB usage figures for 2001 are detailed in Table 4.3 below. As a large number of electrical devices are also used in the routine operations of field personnel for data collection, navigation and communication, small petrol powered generators and batteries are also used for electricity supply.

2001 figures	*Litres of SAB diesel fuel used per year*	*Tonnes of CO_2 per capita released per year*
Antarctic shipping	3,662,500	310.49
Casey station	589,950	63.84
Davis station	606,557	49.50
Mawson station	603,779	72.50
Macquarie stations	219,733	21.85

Per capita figures based on population statistics for the station in the relevant year.
Table 4.3: fuel usage statistics for Australia's stations and vessels (2001) [5].

The fuels used in the Australian program are delivered by ship either in bulk liquid form within the ship's own storage tanks, or in smaller drums and containers. The fuels are transferred from a ship to store tanks and areas at the stations using a variety of methods, including hoses run over the water or sea ice for bulk fuels and barges, helicopters, and over-ice vehicles for containerised fuels. An Australian station will generally store 1.5 years of fuel supply for power generation and the expected fuel usage for vehicles over the coming year. This can easily amount to over 1 million litres of fuel transported and stored at each station per year.

The transport, transfer and storage of such quantities of fuel in the Antarctic environment embody a range of environmental and occupational health and safety risks. However, well defined procedures have been developed to minimise the associated risks and no significant issues have occurred so far.

The critical performance requirements of the energy systems used to support the AAD's operations include cost effective operation, reliability, safety, flexibility, access to maintenance facilities and personnel, and robust performance in the harsh polar environment. The conventional energy systems (fossil fuel powered) used by the AAD are very successful at meeting almost all of their needs and address the critical performance requirements well. However, conventional systems have failed to deliver adequate solutions for a number of science-related activities, such as providing power to remote tidal monitoring sites. Solutions to these failings have included using alternative technologies such as batteries and solar panels, modifying the science objectives to a program that can be supported by conventional technologies, or not undertaking the research.

In addition to the above critical performance requirements, the Australian Antarctic community also regards the environmental performance of their operations as a critical issue due to the value of the Antarctic region as a unique and pristine wilderness area and applies extensive environmental management strategies to all activities undertaken by the community. These strategies can influence the selection of energy systems used in operations, although conventional energy systems are generally permitted from an environmental perspective in almost all situations.

The Australian Antarctic community's commitment to continuously pursuing more sustainable practices is well illustrated by the successful installation of substantial renewable energy generating facilities at Mawson station, Antarctica, in 2003. Two 330-kW wind turbines now displace approximately half (300 kL p.a.) of the diesel fuel previously consumed by the station – the largest renewable energy generation project on the continent – and represent a major achievement for the use of sustainable energy systems in Antarctica and other remote, harsh and sensitive regions [21]. The installation of the turbines follows several decades of evaluation and subsequent implementation of other renewable energy technologies on a smaller scale throughout the AAD's operations, including the use of solar water heaters, passive solar heating, smaller wind turbines, and photovoltaic (PV) power systems [21, 29, 30].

The increased use of renewable energy power generation sources, particularly the large-scale turbines at Mawson, is only one component of a more ambitious and long-term plan to achieve substantial reductions in the use of imported fossil fuels to support the research activities in Antarctica. Other components include developing highly efficient energy systems and operating sophisticated management programs for equipment and users [30].

It is interesting to note that the wind turbine project originally designed to utilise three 330 kW wind turbines, and was subsequently assessed and funded on this basis. The station energy system was upgraded to accommodate three turbines. Foundations for three turbines were constructed onsite, and three turbines were ultimately purchased and transported to Antarctica. Unfortunately a disruption to the shipping schedule, as often happens with Antarctic operations, cut short the time available to install the three turbines in the nominated summer period. Two turbines were successfully erected and commissioned, and plans were developed to install the final turbine in the following year. Equipment, including a ~$1 million-vehicle crane for erecting the turbines, was kept at the station with the uninstalled turbine. After three summers without installing the third turbine, a swift decision was made by the AAD management in early 2006 to bring the crane and turbine back to Australia for sale. This decision was made despite the successful commissioning of the two operating turbines and solid evidence that they were offsetting significant volumes of fossil fuels at the station [5]. As of September 2007, the turbine remains unsold and in storage at the AAD's facilities in Tasmania [31]. No information is publicly available about the decision to reduce the size of the wind turbine project.

The engineering section within the AAD, which was responsible for the turbines and the preliminary analysis of related technologies, is also mindful of the need for renewable energy storage facilities. Research conducted in collaboration with the University of Tasmania over a decade ago [32] predicted that hydrogen energy technologies, particularly if coupled with renewable energy technologies, could play an important role in the future of Antarctic energy systems. However, hydrogen technologies were judged to require another decade of technical development. A new study in 2001 by Pointing confirmed the feasibility of hydrogen energy systems serving the Australian Antarctic program [33], and identified that hydrogen technologies had progressed significantly in the preceding eight years and were rapidly approaching commercial viability. The study also highlighted the need for detailed investigation into the many non-technical aspects associated with introducing this new technology to ensure the efficient, timely and safe implementation of hydrogen energy in Antarctic operations.

The latter study also identified that the strong environmental focus and current high energy supply costs for operations by the Antarctic research community made it well suited to serving as a test bed for the implementation of sustainable energy systems based on renewable and hydrogen energy technologies, with the resulting experiences applicable to other applications. The main conclusions were that the issues related to the emergence of hydrogen as a technically viable energy carrier need to be coupled with the growth in the use of renewable energy technologies in Australia's Antarctic operations and the recognition that an energy carrier is required to further the use of such technologies.

The AAD's involvement with hydrogen has progressed further as a direct outcome of the efforts of this current research project, with a small-scale demonstration/evaluation of a wind-hydrogen energy system at Mawson station in Antarctica . Funding for the project was established after the author outlined the project concept in a briefing provided to the Australian Government's "Australian Greenhouse Office" (AGO) in April 2003. The briefing presented three concepts: the long-term benefits to the Antarctic community of developing practical experience with renewable energy storage technologies, the potential to transfer the experiences or concepts to other remote communities in Australia, and the apparent possibility to fund the initiative using existing finances that were allocated for replacing diesel power systems with renewable energy systems in remote communities. The briefing was well received and the relevant Federal Government Minister announced a funding initiative of $500,000 for the AAD and University of Tasmania a short time later. As of July 2007, the demonstration system is operating to a limited extent – hydrogen 'fuel' is being produced via electrolysis from excess wind energy and the hydrogen is stored in composite material high pressure tanks. A dual-fuel (H_2 or LPG) cooking stove has been installed at a field camp near the station, and a 2 kW low-temperature fuel cell has been installed at the station to contribute to the power demands of a hydroponics greenhouse facility. A four-wheeled motorcycle (quad) has also had the combustion engine converted to operate on hydrogen fuel [31].

4.7.4 A long-term perspective of energy-supply issues for Australia's operations

The Australian Antarctic program is currently going through a period of significant change to its operations, such as the development of an air transport system that will markedly alter the process of deploying people and equipment to the continent. In partnership with the air transport program is a shifting of scientific priorities to new regions of interest that are not as geographically convenient to the existing stations as many activities in the past. These changes will influence the demands placed on the energy supply systems of the AAD, particularly in the long-term. Some possible issues that will be of strategic importance to the AAD in terms of energy systems include:

1. Changes to the planned scope for scientific activities will require more transport within the continent and the use of temporary accommodation systems; this will have impacts on the selection and approach to operation of energy systems to the current 'station-based' model.
2. Conflicts are emerging in the 'style' of operations between the rapid deployment of personnel and equipment by the new air transport system, and existing method of slow, heavy ship and land deployment. This raises the question of what impact will conventional methods of delivering drums and tank loads of liquid fuel have on these plans, and can more flexible energy systems that use renewable resources serve a greater role than at present?
3. As demand for ship-based deployment is reduced, how may the actual cost of fuel delivery be impacted and what constraints may the demands for regular fuel deliveries have on a plan for more flexible operations (given that current delivery costs are absorbed in the cost of delivering people and equipment to the stations)?
4. The changes in scientific scope and development of the air transport system will require more in-field refueling of vehicles and equipment. If conventional energy systems are used, this will increase the risk and likelihood of subsequent contamination of remote sites through fuel spills (and exhaust emissions).
5. Remote sensing technologies are rapidly developing, which is providing an increased capability for scientists to develop more comprehensive experimental activities. Will conventional energy systems be able to support these activities? If the entire reason for presence in Antarctica is scientific research, should not the best energy systems be used even if a change in behaviour is required?

Potential energy-related issues may also emerge in the future from external contexts that could impact Australia's Antarctic operations, such as:

1. Interpretation of the Antarctic Treaty System and the Madrid Protocol could become more strict with regards to fossil fuel usage and impacts, particularly if a significant fuel spill were to occur.
2. International or national policy mechanisms could impose pollution-related taxes on fossil fuels, further increasing the cost of energy for Antarctic operations.
3. As conventional fuel prices rise and Antarctic energy costs increase proportionally, these costs are currently met using existing budgets or specific for budget increases to meet rising energy costs are submitted. Can Antarctic operations continue to expect such budget increases indefinitely, particularly with competing and similar energy-related claims for budget increases from other government sectors such as defence and healthcare?
4. Speculation about supply constraints for fossil fuels could restrict the ability of the AAD to purchase adequate fuel supplies in bulk volumes in the future.

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Chapter 5. Selecting appropriate energy supply solutions

Chapter 2 demonstrated that the consumption of energy is an essential element of modern life, with many of the varied facets of human existence such as education, health, commerce and recreation, all needing or potentially being improved by an element of energy use. With this global need for energy supply, however, modern societies are faced with two sizeable challenges – to develop and implement energy technologies and systems that can provide communities with energy supplies that are accessible, available and acceptable; and to ensure that these energy solutions are delivered in a sustainable manner.

For any energy use situation a wide variety of options can be identified to provide technically viable energy supply solutions. Consequently, the additional challenge arises of selecting from the range of possible technical options the solution that is best suited, or most "appropriate", to the particular needs of the energy-using community that the system will ultimately serve. Such appropriate solutions can be selected through detailed analysis of the needs and capabilities of the energy using community, and subsequent identification of the best technical solution for the community based on their specific situation.

A failure by society to ensure that 'appropriate' solutions are selected can result in a number of adverse consequences, including the advocacy of systems that appear to offer viable energy supply solutions but ultimately result in an inability to meet the goal of providing accessible, available, acceptable and sustainable energy solutions. These 'inappropriate' solutions can appear attractive to a community – or to the system developers – but can ultimately fail to best meet the needs of the users through faults such as being overly expensive or complex, delivering services beyond the needs of the community and consequently consuming unnecessary recourses and funds, or requiring skills and resources for operation and maintenance that are beyond the capabilities of the user community. These inappropriate solutions also project a false image about the viability and characteristics of such systems that discourages the use of alternative energy solutions by other communities.

This section examines the challenges of selecting appropriate energy supply solutions for communities while striving to develop solutions that are more accessible, available, acceptable and sustainable. The material has been adapted from a paper prepared by the author for the World Energy Congress *Youth Symposium* in 2004 on appropriate energy solutions [1]. The original paper included analysis of the appropriateness of hydrogen energy technologies for Antarctic communities.

5.1 A whole-of-system approach to developing energy supply solutions

Modern societies use energy in an extremely wide variety of ways. Examples of the diversity of energy using applications include small battery-powered electric devices such as mobile phones, the broad range of vehicles that operate on fossil fuels, or the large and small communities using heat and energy to operate homes, businesses and community services.

All energy-consuming applications, such as these examples, are served by energy systems, with the systems composed of several key elements that function in partnership to ultimately meet the energy needs of the user. These elements include the physically obvious technological components, but also include 'softer' elements that bear an important influence on the design and operation of an energy system. The common key elements of energy systems are outlined below, and are illustrated graphically in Figure 5.1. The concepts included in the list of elements are further explained through an example of the energy system associated with a common electrical device – a mobile phone.

To ensure that energy needs of a user or community are met, the design and selection of energy systems must identify and consider each of these key elements and their subsequent integration to provide viable and appropriate energy supply solutions. This technique of identifying and evaluating the role of the key elements in an energy system is defined in this paper as a "whole-of-system" approach.

The key elements of energy systems commonly include:
1. The source of primary energy
2. The series of energy technology components associated with the conversion of primary energy to more functional forms of energy (such as electricity or mechanical power), and the subsequent distribution and/or storage of this energy.
3. The energy-consuming devices or processes that operate in the system and contribute towards achieving the objective of the system
4. The management systems and strategies used to control the resource consumption and the energy technologies
5. The user/operator of the system and their circumstances, including how much power the user requires, their methods/habits of energy use, their capabilities and resources to operate, maintain, and finance the system, and their values.

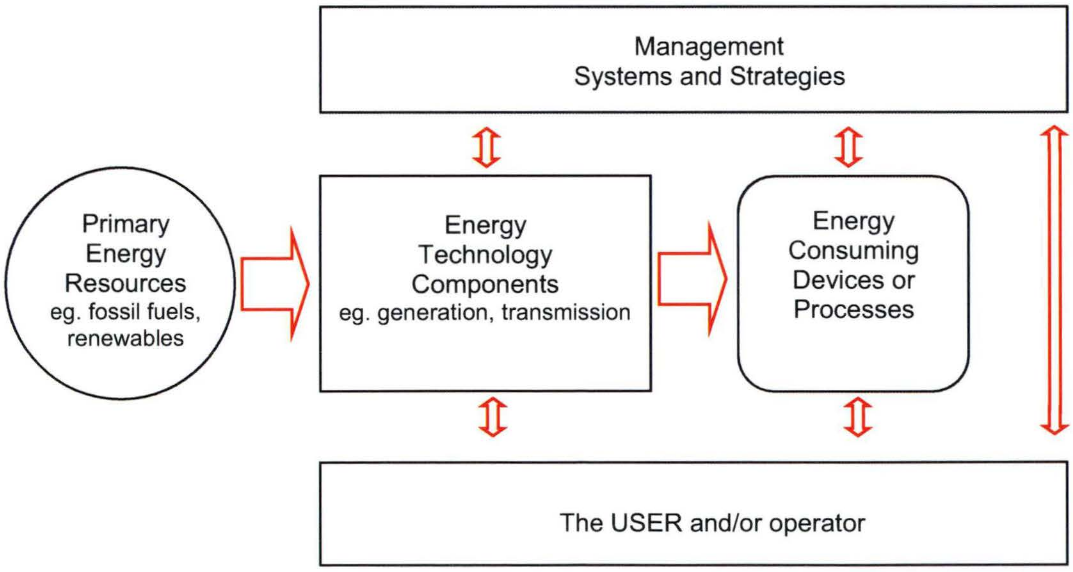

Figure 5. 1: the key components of an integrated energy system.

Within this whole of system approach to viewing energy systems, the fifth element (the user/operator) holds a unique position – they are the reason for the existence of the system and so define the performance requirements and critical constraints of the system to which the other elements must comply, yet they too are an important element of the system and can influence the operating performance of the system through their own behaviour.

A practical constraint to applying whole-of-system perspective to the selection of energy systems is that it is not always feasible for a party to influence control over all of the elements of an energy system. The example of the energy system of a mobile phone is reviewed in Table 5.1. The example demonstrates that if the user were hoping to improve the performance of their system they would have little direct influence on the primary generation sources or the technologies and management of the domestic electricity grid in the local area (the island state of Tasmania). However, even when the options available to affect change in an energy system are limited, progress towards improved energy system performance can still be achieved via improvements in even a single element of a system. For the mobile phone user, changes to the phone usage patterns, the times of phone charging (off-peak), or even the purchase of a new phone, all offer opportunities to change the total performance of the energy system and don't require change to the other elements of the system.

This example identifies the individual elements of the energy system associated with a common mobile phone. For the point of the example, the device is specified as operated by the author for domestic and business purposes in the Australian (island) state of Tasmania. The device is powered by an internal rechargeable battery that is connected as required to the domestic energy network for charging. The primary energy source in the system is the source of the energy ultimately used to charge the phone battery – in Tasmania practically all electricity is generated from renewable hydroelectric or wind power, consequently these renewable resources are the primary energy sources for the system. The related energy technologies in the system include the wind or hydroelectric turbines that turn the primary energy into electricity, the Tasmanian electricity distribution network and the domestic connection to that network, the charger supplied with the phone, and finally, the battery in the device. The energy consuming devices are the electronics in the phone. The management systems inherent in the system include those related to electricity generation from wind and/or hydroelectric power, the electricity distribution systems, and the energy management software in the phone controlling functions such as standby. The user/operator of the system is the owner of the telephone, who is responsible for operating, charging and maintaining the device; and who has defined needs for the phone performance, user habits, technological understanding, environmental values, resources and capabilities. These elements are directly associated with the operation of the device, and a failure in one element would impact the operation of the system as a whole. For the mobile phone to effectively serve as a communication tool, the user must also interact with other systems, such as that used to support the transmission network infrastructure (base stations etc) or the phones of other users. Consideration for these peripheral systems is not the responsibility of the user, but would be of interest to a telecommunications company as their absence would impede the value of the mobile phone as a marketable product.

Table 5. 1: Example 1; the complete energy system of a mobile phone.

In the mobile phone example, however, the whole-of-system approach also offers advantages to the user over narrower approaches [2] as the method identifies all the elements that can influence the performance and operation of an energy system – even those that can't be influenced – and through this recognition provides opportunities to leverage changes in peripheral energy systems. For example, developments in other energy systems such as Tasmania joining the (Australian) National Electricity Market (NEM or NEMMCO) [3] may have an influence on one or more of the elements of the mobile phone energy system. Via the NEM, the user may have the choice to purchase power at a different rate from other suppliers in Australia or a different source of primary energy may become available (solar/PV, natural gas etc). In this way the user could exert control over an element that is current fixed (wind/hydro electricity generation in Tasmania) or alter their user habits to leverage changing energy tariffs.

As examined further in Example 2, the mobile phone user will have to select from a range of possible options those which best meet their energy needs and deliver an energy supply solution that adheres to their values, capabilities, resources and interests – essentially, they will have to select the most appropriate energy supply system from the options available.

The whole-of-system approach to energy systems is an effective foundation for the selection of energy systems to meet the needs of specific energy users – including systems for new applications, or the selection of improvements to existing systems to offer enhanced performance and/or sustainability. In doing so, a process is applied by the parties involved in the system selection (the 'selectors' [4]) to identify the key elements of the system and the various methods by which those elements could be provided, to evaluate how the various options for each element would impact the performance that individual element and the performance of the system as a whole, and finally to select the best possible combination of elements (whole-of-system) for the application.

As modern society can offer a wide variety of options (technologies, methods, etc) for each element of an energy system, a complex array of possible energy system solutions can be developed for any specific energy application. Even for the selection of new energy systems where the process is relatively straightforward [5], selecting from the potentially wide variety of options for system designs poses a challenge to the system selectors. If improvements to the performance of an existing energy system are sought, the challenge broadens to deciding if the existing system should be improved or replace, and if improved - what possible improvements and to what aspects of the system. In each of these situations, the challenge ultimately faced by the energy system users and developers is to select from the wide variety of available options the solutions that are most appropriate for the users, while working within the real-world constraints of the energy systems and user communities.

Example 2, in Table 5.2, examines the variety of options available to meet the energy needs of a remote community that generates stationary electrical power from diesel electric generators operating on imported fossil fuels. The number of options and the variation in their complexity and potential impacts illustrates the challenge that would be faced by the community in selecting which solution(s) would be best for their needs, and serves as an introduction to the next section which examines the identification of appropriate energy supply solutions.

Options to improve the performance of a remote community's power plant

For a small community located in a remote region of Australia, the stationary power demands of their houses, buildings and industries are met using a conventional power plant of diesel electric generators with a small 'mini-grid' providing electricity to the community. The power plant is controlled by a basic energy management system that controls the output of the generators to meet variations in the energy demand (within specific maximum and minimum power outputs). The generators are fuelled with a normal diesel fuel that is imported from a wholesale supplier located a reasonable distance away. The system provides electricity for heating, lighting, and domestic, commercial and industrial devices in the community. Individuals in the community are charged for their energy use on a simple tariff of cost per kWh of energy consumed. The community is seeking to improve the environmental performance of their energy system, reduce the operating cost, and enhance the security of their energy supply. To achieve these objectives, the community has a number of options that relate to specific elements of their existing energy system or to the energy system as a whole (e.g. replacement).

Some of the obvious options available to the community include:

1. Install state-of-the-art fossil fuel based power generation systems that offer improvements over generic systems, including high efficiency, ultra-low emissions, etc.
2. Upgrade components of the energy system to reduce energy use and improve the system performance (e.g.. Energy efficient devices, robust distribution systems, capture of waste heat, insulation of equipment, buildings, devices to reduce heating/cooling demand etc.).
3. Introduce improved fuel blends, including options such as low-contaminants fossil fuels (e.g. Low sulfur diesel), gaseous fuels (LPG, CNG), or the partial or full introduction of fuels produced from sustainable resources (hydrogen, methanol, bio-diesel etc.).
4. Integrate power generation technologies that utilise local renewable energy resources, in partnership with conventional energy systems (e.g. Wind-diesel, PV-diesel etc.).
5. Install energy supply systems wholly dependent on local and sustainable energy resources. (e.g. Passive solar heating, photovoltaic or wind electricity, local bio-fuel production etc.).
6. Implement improved energy systems management techniques to reduce and balance energy demand (e.g. Demand side management, peak load shedding, off-peak utilization)
7. Undertake user education programs to contribute to management strategies and reduce total energy demand and excess loading on the energy system.

Table 5. 2: Example 2; Options to improve the performance of a remote community's power plant.

For the example of a remote community presented in Table 5.2, each of the solutions reviewed offers some benefit(s) to the user community, but also comes with economic, resource and environmental costs, will place new demands on the capabilities of the user community to understand, operate and maintain the system, and will offer advantages and disadvantages over alternative solutions.

The following section presents a method by which a solution can be selected that provides a technically viable energy supply system that also matches the broader needs and capabilities of the energy using community – essentially this is a process to select the most "appropriate" solution from the long list of possible options.

5.2 *Identifying 'appropriate' energy supply solutions*

Appropriate: Suitable for a particular person, condition, occasion, or place; fitting [6]

Appropriate energy solution: a combination of energy technologies and management strategies that are capable of meeting the practical needs of an energy using community and respect the values, needs, capabilities, resources and circumstances of the community.

As outlined above, energy systems are composed of several elements, including the primary energy sources, the technologies required for energy generation, distribution, and consumption, the methodologies and approaches to managing the system, and the end users and operators of the system. The identification of an energy supply solution that is appropriate for a particular situation requires consideration of all of these elements. This paper presents a process which focuses on evaluating how these individual elements can influence the measure of appropriateness of an energy supply solution from two perspectives - technical and social (user) perspectives.

5.2.1 Technical perspective of energy systems

The motivation for the investment of finance, resources and effort in the development of any energy system is to meet the needs of a user in achieving a specific objective or undertaking a specific activity. Therefore, the critical requirement of any energy system from a technical perspective is that it must be physically capable of meeting the energy needs of the user for which it is being developed. Ultimately, any solutions selected for inclusion in an energy system must not restrict the capability of the system to meet the specific energy demands it is designed for. An energy system may also have other technical requirements that must be met, such as the integration of existing infrastructure, the use of specific equipment or processes (such as for demonstration of new technologies), or an inherent level of flexibility to meet future changes in energy demand or technology development.

5.2.2 Social or User perspectives of energy systems

Energy systems are tools, developed to serve the needs of individuals or societies, without adversely influencing the behaviours and activities of the energy users. Therefore, from a user perspective, the process of selecting the components of an 'appropriate' energy system must take into account a number of factors, including:

1. the values of the user community and their relationship to energy systems and methods of energy supply,
2. the objectives or purpose of the community and the importance and role of energy systems in meeting this purpose,

3. the capabilities and resources of the community to purchase, understand, operate and manage technologies – particularly those relating to energy systems,
4. the ability of the community to adapt to new technologies and processes,
5. the availability of local resources (energy and support resources), and
6. the true nature of the current and future energy needs of the community.

While it is possible for a number of different energy supply solutions to be viable and hence appropriate from a technical perspective, it is the user or social element that will most critically influence the measure of how appropriate a particular solution is to a given user community. In order to evaluate the technical solutions on their ability to meet the social needs of the community requires a detailed understanding of the energy using community.

The following process of identifying technical solutions, eliminating non-viable options, and selecting the most appropriate solutions energy solutions was developed as a result of research into the implementation of appropriate energy technologies into Antarctic operations. Further details of these studies and a case-study evaluation of Antarctic energy systems follows in later sections of this paper.

5.3 A process for selecting appropriate energy supply systems:

When seeking to develop a new energy supply system (or make improvements to the performance of an existing system) for a specific application and user community, the following steps are advised:

1. Develop a comprehensive understanding of the needs, capabilities and circumstances of the user community through direct engagement with the community.
2. Broadly identify the potential energy supply solutions that are capable of meeting the needs of the community from a technical perspective, including solutions for the individual elements of the energy system and the system design as a whole.
3. Examine the relationship between the characteristics of the technically viable solutions and the characteristics of the user community to broadly eliminate solutions that conflict with the needs or capabilities of the community. Subsequently produce a short list of viable and appropriate solutions.
4. Refine the technical analysis of the short-listed solutions to enable a detailed comparison of the system designs, technical performance and other critical factors such as cost, technical complexity, and environmental impact.
5. Compare (and rank) the performance of the short-listed solutions relative to their ability to comply with or meet the needs, capabilities, values and circumstances of the community. The resulting list should provide a ranked set of technically viable and socially appropriate energy supply solutions for the particular user community.
6. Engage with the user community to evaluate the results of the study and select an appropriate solution from the short-listed candidates.

A comprehensive understanding of the energy user and their particular situation can be successfully developed by a number of methods, including direct engagement with the community or external review of their behaviour, operations and values. Undertaking direct engagement with the users may involve interviews with individuals and groups, monitoring of existing energy use patterns, and demonstrations and evaluations of new technologies or management strategies. The information gathered can be applied to develop a comprehensive profile of the user. The engagement with the user can also serve as a valuable forum to inform the community of the objectives and methods of the energy system evaluation being undertaken and to inspire the positive involvement of the community in the process. Establishing a solid foundation of open communication with the community will enable the system selectors to present and preliminarily evaluate some of the possible solutions that may be considered for use as a first step to identifying potential concerns or introducing new concepts to the user.

The user profile is subsequently used to define the broad performance specifications of the energy systems and to identify critical constraints to the system design, such as cost, complexity, and environmental impact. The next key step in the process is to identify, in alignment with the basic principles of sustainability, the availability of local resources (particularly renewable resources) that may influence the design and operation of the system. Based on the identification of the system performance requirements, possible constraints and availability of resources, possible solutions for individual system elements or broad concepts for system designs can be identified.

Selecting the most appropriate and technically viable solution (new component, new system, new strategy etc) from this potentially large list of possible solutions requires careful consideration of the 'user profile' and comprehensive analysis of numerous possible technical solutions. The details of the specific user's circumstances and the experience of the system designer should enable a short-list of potential system designs to be quickly developed, but the specification of a detailed system design will require detailed analysis of the energy system components and user demand.

A well-respected method of undertaking such analysis is via theoretical modeling using computer software, and a wide variety of tools are available. Two products that have been applied in the Antarctic energy use investigation are HOMER [7] and HYDROGEMS [8], the former a free, relatively low resolution but easy to use tool and the latter a very high resolution tool that enables comprehensive analysis of highly complex systems which requires investments in software and training time.

The detailed technical solutions developed via methods such as modeling should then be evaluated relative to their ability to comply with or meet the system constraints identified through the user profiling process. There are a wide variety of methods available to achieve this – one process applied by the author has been to develop a matrix of the performance of the solutions versus the key user constraints, with numeric performance scores awarded to each solution. Weighted values were applied to each constraint to indicate the relative importance of different constraints (e.g. Importance of economic cost over environmental impact for the community), and the subsequent totals for each solution enabled an 'appropriateness' ranking for the different solutions considered [9].

5.4 *References:*

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3. National Electricity Market Management Company Ltd, 2004, An Introduction to the National Electricity Market, 1 Aug, http://www.nemmco.com.au/about/000-0187.pdf.
4. The parties involved in the selection of an energy system would potentially include (depending on the size, scope and purpose of the system) the engineers and technicians, policy and government representatives, the user group, the broader community, and others.
5. Perhaps defined as: "to select the best possible technologies and processes for each system element to assemble into the best possible combination of solutions to meet the requirements of the system, within the constraints of the system".
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Chapter 6. Developing the Research Tasks

This chapter presents the specific tasks addressed in the research. It begins with a summary of the main themes from the literature review and draws the necessary conclusions from the material to identify and define the research tasks.

6.1 Summary of the literature review

The main themes of the literature review can be summarised as follows:

Chapter 2 began with a review of the critical role that energy services play in all elements of modern society. Fossil fuels were shown to currently provide the bulk (~90%) of humanity's energy needs; and consequently almost all energy technologies and systems are designed or configured for operation with these fuels. These conventional energy technologies, although well developed, have failed to meet the needs of a large proportion of the world's population and are not likely to do so in the near future. A range of other concerns relating to humanity's dependence on and the impact of these conventional fossil-fuelled energy systems have emerged and are growing in importance in local, national and international forums. The local and global environmental impacts of fossil fuel use, the long-term security of supply from diminishing resources, and the lack of equal access and availability are the major areas of concern.

Various solutions to address these concerns by modifying factors such as the technologies, their operation, and even the behaviour of the energy users have been identified and are being implemented. Achieving the changes needed to make the energy systems that serve humanity more sustainable is a large and complex challenge. Comprehensive strategies that have been developed at local, regional and international levels are proving to be valuable tools in achieving progress towards the changes needed. UNDP Administrator Mark Malloch Brown succinctly captured the essence of successful strategies with his comments that "we *do* have the resources and technological know-how to rise to the challenge of energy that supports sustainable development" and "doing this will require major shifts in policy – it will not simply happen on its own" [1]. Resources are available to help energy users understand the technical and non-technical actions that could be pursued. A key element of any long-term solution, however, must be the exploitation of alternative forms of primary energy other than from fossil fuels. Technologies that harness renewable primary energy resources are now well developed (and new technologies are under development) and are showing great promise as solutions to the three main areas of concern about conventional energy systems.

The use of renewable energy technologies as a replacement for fossil fuels, however, does present a number of challenges for many common applications. Major challenges include developing sufficient storage capabilities to compensate for intermittent supply and to enable vehicle fleets to operate. Again, a range of solutions are available and are being developed to address these issues. The use of hydrogen as an energy storage medium, or "energy carrier", for a wide range of primary energy sources has advanced significantly in recent decades. Hydrogen technologies have subsequently been described as 'critical technologies' (ones that can bring about a step function effect in the present state of affairs) in relation to sustainability [2] due to their suitability for integration with renewable energy technologies.

The future roles of hydrogen energy technologies in the global energy economy were evaluated in Chapter 3. The concept of hydrogen as an 'energy carrier' and the associated processes and technologies were introduced. Key conclusions include that the hydrogen energy economy concept has been significantly advanced in a technical sense and the practical capability has been demonstrated using a range of methods to produce, store and convert hydrogen 'fuel'. Hydrogen energy technologies subsequently have the potential to play many different roles in meeting the energy needs of modern society, including integration with renewable energy storage systems. Whilst hydrogen technologies do offer many advantages over conventional energy systems, they do face a number of significant barriers at the present time that are restricting their uptake by conventional energy users.

The major barriers to the uptake of hydrogen technologies include: 1. a range of specific technical challenges within the individual technology categories associated with the hydrogen economy; 2. the current costs for energy services from hydrogen systems are too high in comparison to conventional solutions; 3. a very limited amount of supporting infrastructure is available for hydrogen technologies, such as vehicle refueling stations or maintenance and servicing facilities for hydrogen systems; 4. there is limited understanding and support within user communities for novel hydrogen technologies; 5. the additional benefits that hydrogen energy systems can offer, particularly with regards to sustainability, are not valued within conventional economic systems; 6. there is an absence of policies and standards to facilitate the introduction of hydrogen technologies into conventional society; 7. and there is a strong need for the development of practical experience with laboratory-proven systems to enable further product development and refinement and to develop consumer confidence in new hydrogen products. These challenges are far from insurmountable, but are clearly restraining the ability of viable hydrogen energy technologies from entering mainstream markets for energy services.

As with the uptake of renewable energy technologies, the development of comprehensive strategies to drive change has been recommended and pursued by hydrogen technology supporters. These strategies have tended to focus on technical aspects of the challenges due to the relative immaturity of hydrogen technologies. However, as the technologies have matured in recent years the strategies have begun to integrate non-technical issues as well. A common approach to addressing the barriers faced by hydrogen technologies is to focus on niche applications for the development of early adoption markets. Similar approaches were commonly applied (and are still in use) for the early commercialisation of renewable energy technologies such as solar (photovoltaic) panels. For both hydrogen and renewable energy technologies, communities in remote locations are suggested as early markets. Reasons for the attractiveness of remote communities were cited as: they have naturally higher energy costs due to the larger burden of fuel delivery costs, potential for cleaner local environments and high profile impacts from emissions, improved opportunities to measure social development impacts due to smaller community population sizes, and potentially a lack of adequate or competing existing infrastructure.

Since the commencement of this research in 2002, several demonstration and research projects have applied this strategy of focusing on remote communities and developed wind-hydrogen energy systems for communities in the Arctic and sub-Arctic regions [3, 4]. The technical successes of these projects and their positive impacts on non-technical issues relating to hydrogen energy uptake raise the obvious question of how efforts to implement hydrogen technologies in Antarctic may relate to the broader need for early adopter markets for such technologies.

Chapter 4 subsequently provided a broad overview of the international community of scientists who work in Antarctica and the legal, environmental and operational parameters that apply to their activities. The overview, and associated case study of the Australian Antarctic program, indicates that several possible motivations exist for Antarctic communities to pursue more sustainable energy solutions than the fossil fuels that are predominantly used at present. They include the extremely remote location of operations and associated energy supply costs, the local environmental impacts of fuel storage, transfer and use (including spills), the long-term security of supply of fossil fuels, and the limited performance of conventional energy technologies in serving the needs of scientific programs. These motivations have driven the Australian community to capitalise on the potential of renewable energy systems to enable more sustainable and secure energy systems as part of a broader program to reduce dependence on fossil fuels. The Australian Antarctic program has also already begun investigating how hydrogen technologies may be used in their operations and specifically requested assistance from this research project on some key questions. Although the Antarctic community's interests are very self-serving in investigating hydrogen energy technologies, the valuable outcomes from other small-scale demonstration projects in remote communities around the world suggest that there must be some value in extracting knowledge from the Antarctic experience. Antarctic energy operators can also gain useful knowledge from the experiences of other communities.

Chapter 5 examined in detail the concept of selecting 'appropriate' energy technologies for specific solutions, building on from the review of how and why conventional energy technologies have failed to provide appropriate solutions for a large proportion of the world's poorer populations. The approach presented outlines how all the key elements in an energy system and their integration must be identified and considered during the design and selection of energy systems to ensure that the energy needs of a user or community are appropriately met. The key elements in energy systems were cited to include: 1. the source of primary energy; 2. the series of energy technology components associated with the conversion of primary energy and the distribution and/or storage of this energy; 3. the energy-consuming devices or processes that operate in the system; 4. the management systems and strategies used to control the resource consumption and the energy technologies; and 5. the user/operator of the system and their circumstances, including how much power the user requires, their methods/habits of energy use, their capabilities and resources to operate, maintain and finance the system, and their values. A six-step process was also presented with suggested practical actions for securing the information required for a specific situation and energy-using community.

The concept of selecting appropriate energy technologies is highly relevant when considering the introduction of innovative energy technologies and systems, particularly hydrogen, in any energy-using community. For the international Antarctic community, the selection of inappropriate energy systems could have dire (if not deathly) consequences if the energy systems were to fail in the freezing polar environment. Ensuring that appropriate technologies are identified and introduced in an appropriate manner is therefore critical for Antarctic operators. Previous research and practical activities undertaken within the Australian Antarctic community, including prior work by the author, have addressed some of the tasks in the 'six-step process' presented in Chapter 5 for evaluating and identifying appropriate energy technologies [5-8]. There is now a need to specifically apply this analysis to the use of renewable and hydrogen energy technologies in their operations.

6.2 Conclusions from the literature review

There is a clear need for changes in the design, operation and fuelling of the world's energy systems. This applies on a global scale, but is also directly relevant to the operations of small and independent communities (such as Antarctic research bases) around the world and in the developed and developing world.

There are a range of options available to enable these changes. Renewable energy technologies are key elements of more sustainable energy systems and energy storage components are essential when renewables are used. Hydrogen is seen as a critical solution to the storage challenge, but early adopter markets are needed now to assist in proving and improving the technologies or the role of renewable energy technologies in global energy systems will also be constrained.

In the specific context of this research project, the Australian Antarctic community has advanced through these options such as with successful programs to achieve better management and efficiency of energy use through technology and user behaviour changes. They have also introduced renewable energy technologies in a range of applications, including the relatively large turbines at Mawson station. More significant penetration of renewable energy resources into their operations is constrained by needs for energy storage and the supply of vehicle fuels. This mirrors the global challenge facing renewables. The Australian community is already considering the use of hydrogen as an energy carrier, and as a consequence of this research project, is now developing practical experience.

This vigorous pursuit of more sustainable energy systems for their Antarctic operations suggests that the Australian Antarctic community has the culture, capability, skills and resources to evaluate and implement relatively innovative energy technologies. Given that research and testing of energy technologies is not a formal role of the Australian Antarctic Division (AAD), the Government's lead agency for Antarctic affairs, then it can be assumed that the community has strong motivators to operate more sustainable energy systems.

In a theoretical context, strategies are needed for management of the changes associated with developing more sustainable energy systems. Strategies must address technical and social issues. The issues can be global such as environmental impacts or the need for supporting infrastructure for technologies, or more specific to individual communities such as the harsh Antarctic environment and legal regime of the Antarctic Treaty System for the AAD. The AAD seems to lack an overall strategy with regards to their energy services, as demonstrated by the commissioning of a wind energy project with three turbines and the removal of one turbine (without even completing installation), as well as their response to securing external funding for the hydrogen demonstration project. Previous research has indicated that non-technical issues are critical in regards to evaluating and implementing hydrogen technologies, and that these issues will have a significant impact on the evaluation and implementation of hydrogen technologies in Antarctic operations. Therefore there is need to develop energy-related strategies within the Australian Antarctic community.

It is important to consider the appropriateness of proposed energy solutions for communities. Evaluations must include the characteristics of the community and the operation and performance of the energy technologies. With respect to energy use in Antarctic, previous efforts have led to the point where detailed analysis of the appropriateness of hydrogen technologies is needed, and subsequent development of strategies to further evaluate and/or implement new technologies.

These previous studies, the pragmatic perspective of Antarctic operations and existing experience with renewable energy technologies also put the AAD in a position of seeking detailed technical analysis of their ambitious plans for renewable energy-powered operations such as at Mawson station.

Through this research and the Australian Antarctic community's proactive examination of the potential use of hydrogen energy in their operations, a viable and possibly valuable early market for hydrogen technologies may be emerging. This raises the questions of 'if' and 'how' the future of the hydrogen energy economy could be influenced through the use of hydrogen technologies in Antarctic communities, and what benefits or costs may there be for the stakeholders involved if Antarctic communities were to actively pursue recognition as early market adopters. The strong motivations of Antarctic communities to develop more sustainable energy systems and their proven capabilities to evaluate and introduce innovative technologies suggest that they may be very suitable as early adopters. The viability and value of transferring experiences from Antarctica to other regions must be further explored, however, before such conclusions can be confirmed.

6.3 Research Tasks

Accordingly, the following are identified as the prime research tasks in this study:

1. To conduct a comprehensive evaluation of the roles that hydrogen energy technologies can play in the Australian Antarctic communities operations, specifically when coupled with renewable energy technologies.
2. To perform a detailed engineering analysis of the technical viability of using hydrogen technologies for large applications in partnership with renewable energy technologies. The analysis should aim to be as 'real world' as possible to provide the AAD with highly relevant information to guide their future ambitions with Mawson station. The analysis should subsequently indirectly test if and how such real-world analyses can be conducted at the present time.
3. To engage with the Australian Antarctic community to identify and understand the non-technical issues associated with the evaluation and implementation of hydrogen technologies, and to enable assessment of the appropriateness of hydrogen technologies for the community.

6.4 References:

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Chapter 7. Roles for hydrogen energy in Antarctic Operations

This chapter provides a broad overview of the many and varied types of energy-consuming activities that are undertaken during Antarctic research expeditions, and identifies potential roles for hydrogen energy technologies in delivering energy services in support of these activities.

The chapter also illustrates that the diversity of choice in where hydrogen technologies can be used and the range of related opportunities and potential issues will present challenges to Antarctic communities in identifying when, where and how to implement hydrogen technologies.

The analysis presented in this chapter is based on a forward looking assessment of how hydrogen technologies could perform when they reach commercial maturity, rather than the current status of technologies (as presented in Chapter 3).

The applications and potential roles that are reviewed include:

1. Large scale permanent facilities – Antarctic research stations
   a. Centralised energy storage
   b. Decentralised energy storage
   c. Generation of transportable fuel
2. Temporary and small scale research camps – Antarctic field camps
   a. Stand-alone energy systems
   b. Supported energy systems
   c. Emergency energy systems
   d. Automated research and operational equipment
3. Antarctic transport systems
   a. Primary (mobility) and auxiliary (other energy demands)
   b. Direct use of hydrogen as a fuel in the primary power system of a vehicle
   c. Use of hydrogen as a fuel additive to conventional fossil fuels
   d. Periods of peak load in partnership with conventional primary power systems
   e. Meeting auxiliary energy demands
4. Personal or mobile devices
5. Automated research and operational equipment

For each application, the nature and objective of the activity, and any relevant details that may influence the selection of energy system are reviewed. The required energy services and current methods of supply are described and the strengths or faults of these solutions are evaluated.

The author's professional experience as an engineer working in polar environments was combined with knowledge of hydrogen energy technologies generated through the literature review and subsequent studies to investigate the potential roles of hydrogen technologies. Issues that are evaluated for each application include: how hydrogen technologies can meet the user's operational requirements, including comparison with existing solutions; identification of specific technologies that may be used and in what roles, including examples of operating or manufacturer 'flagged' products; identifying potential impacts and benefits or potential issues and problems; identifying how the situation may be relevant to other users or applications; and evaluating how the development of other technologies (e.g. renewable energy technologies, communications, remote sensing, etc.) may contribute to expanded capabilities for hydrogen technologies in the applications in the future.

7.1 Large scale permanent facilities – research stations

Permanent Antarctic research stations play key roles in the international science programs undertaken in the region, including providing infrastructure for science activities undertaken on-site and support for expeditions to more remote field locations. Australia operates three relatively substantial permanent stations on the continental coast (and one permanent sub-Antarctic station), contributing to the more than seventy permanent facilities in the region.

The energy demands of permanent stations include heating and power for the station buildings, fuel for station vehicles, and fuel for transport to and the operation of remote science programs (although these can also be independently powered). Fossil fuels are the primary energy sources for practically all Antarctic stations at present, except for Australia's Mawson Station, where wind energy is making an increasingly substantial contribution. With the exception of the energy used in intercontinental transport systems, Antarctic stations represent the largest forms of energy use in the Antarctic region [1].

Table 7.1 illustrates the operational details and energy consumption of Australia's research stations. Since the use of renewable energy resources as a primary energy supply is anticipated to increase at all stations in the future, this study will use Mawson Station as a template for examining the potential roles of hydrogen energy technologies at permanent Antarctic stations.

7.1.1 Mawson Station: a model of conventional operations and energy systems

Figure 7.1 :view of Mawson Station on the Antarctic coast [2].

Australia's Mawson Station (Figure 7.1) is a moderately large research facility located on a rock shelf on the eastern Antarctic coast (67° 36' S, 62° 52' E). The station is operated year-round, with a population ranging from 20 to 60 people. The station is dependent on external supplies of food, equipment and fuel, and is used as a staging point for expeditions departing for the interior of the continent. The site is routinely subjected to gale force winds and sub-zero temperatures, and can only be accessed by ship for approximately 4 months each year.

	Casey	Davis	Mawson
Energy usage			
Population (Summer/winter)	70/20	70/22	60/20
Annual energy consumption (MJ)	14,452,000	14,900,000	16,000,000
Average power load (kWh); Total	4,014,000	4,136,000	4,444,000
Average power load (kWh); Electric	1,803,000	1,888,000	2,011,000
Average power load (kWh); Heating	2,211,000	2,248,000	2,433,000
Energy systems			
Powerhouse	Diesel cogeneration - 4 main generators - 2 emergency	Diesel cogeneration - 4 main generators - 2 emergency	Diesel cogeneration - 4 main generators - 1 emergency
Generation capacity (kW)	1200	750	850
Fuel consumption Litres of SAB p.a.	514,590	523,160	520,000
Heat	Electric/oil fired	Electric/oil fired	Electric/oil fired
Wind	1x 10 kW Vergnet GEV 7.10 turbine - connected to grid - 10,780 kWh/yr - 0.64% station load	Not used	2x Enercon E-30 (300 kW) turbines - connected to grid - 1,288,342 kWh/yr - 25% station load
Solar	Not used	Solahart K-panels 10 kW, 790 litre hot water cylinders	Not used
Storage systems	Not used	Not used	Wind-to-heat water storage system
Energy management	BMCS with 35 networked controllers	BMCS with 41 networked controllers	BMCS with 39 networked controllers
Efficiency measures	- load shedding, - high efficiency lighting - heat used to melt ice for water or saline water preheated prior to reverse osmosis		

Table 7.1: Energy system designs and energy usage for Australia's permanent stations [3].

The station is composed of a number of large, well-insulated and physically-separate buildings that were specifically designed for the environment. Each building serves a specific function, such as accommodation and recreation areas, laboratories, workshops, food and equipment storage, administration etc. The separation of the buildings provides a measure of security in the event of accidents such as a fire, and enables better psychological separation of work and living environments.

The station's energy needs can be separated into electrical and heating requirements. Electricity is essential for tasks such as lighting and operation of plant and equipment in all areas of the station, including the critical operations of communications and medical support. Heating is also needed in all the station buildings due to the low ambient temperatures (generally below freezing) and the further chilling effects of the wind.

These energy needs are currently met with two interconnected sub-systems – a renewable wind energy system and a conventional diesel electric generator (DEG) power station. The total system operation is outlined in Part 1 of Figure 7.2.

In this integrated system, electricity produced by the wind turbines is used to meet the station's electrical energy demands. Excess wind energy is diverted to the station's heating system. Initial studies indicate that the turbines can make a substantial contribution to the station's electrical and heating loads, and there may also be periods with further excess wind energy that cannot be diverted to heating and will require 'dumping'. If the electrical load cannot be met by the turbines, the DEG system uses stored diesel fuel to supply the deficit.

The heating needs of the station are serviced with a reticulated heating fluid that passes through the floor of each building as part of the station's annular site services network. Heat is added to the system via electric boilers fed with excess wind energy, or through waste heat captured from the DEG system. In rare circumstances, diesel-fuelled boilers can also be used for heating. Variable speed pumps distribute the heating fluid from a central reservoir to sites around the system to maintain set temperatures [4].

The entire heating and electrical, wind and DEG, system is monitored and operated by a sophisticated building management and control system (BMCS) that is managed by AAD personnel operating on-site and in Australia (via satellite links) [5].

The current station design and the supporting energy system are both highly efficient due to focused efforts to reduce the station energy demand and optimise the system operation prior to the introduction of the wind turbines. As shown in Table 7.1, the station's electrical and heating demands are consequently closely comparable at 2,011,000 kWh and 2,433,000 kWh respectively, have negligible daily variation and only slight seasonal variation.

The dominant weakness of the current energy system is the continued dependence on external fuel supplies ('Special Antarctic Blend diesel', or SAB). The fuel is known to have an adverse impact on the local and global environment, continues to increase in purchased and delivered cost, and its annual delivery is subject to the availability of an appropriate ice-strengthened vessel, suitable weather conditions, and an absence of sea ice near the station.

The strength of the current system is that it optimises the use of innovative renewable energy technologies (wind turbines) to improve the environmental and economic performance of the station and reduce the dependence on external energy sources, while maintaining access to prior investments in proven energy supply technologies (DEGs) that are commonly used in the region.

At some point in the future, the relative advantages of the DEG component of the current system can be expected to diminish as fossil fuel prices continue to rise, concerns about environmental impacts in the pristine Antarctic region grow, and the performance and reliability of large-scale wind turbines in the region is proven by practical operation.

At such a point, the use of energy systems that are independent of external energy supplies and utilise only local and renewable energy resources will become attractive and potentially viable, including systems that utilise hydrogen technologies for renewable energy storage.

The core roles that hydrogen energy technologies could play in the stationary energy systems of permanent Antarctic stations such as Mawson, are projected to include:

1. Centralised energy storage – storage of excess renewable energy, enabling reduction in the demand for conventional fossil fuels as backup to direct-to-load renewable energy generation.
2. Decentralised energy storage – providing emergency/backup power for specific energy demands, enhancing grid stability, allowing improved management of energy demand, and decentralised storage of excess renewable energy.
3. Generation of transportable fuel - to meet local and remote energy demands.

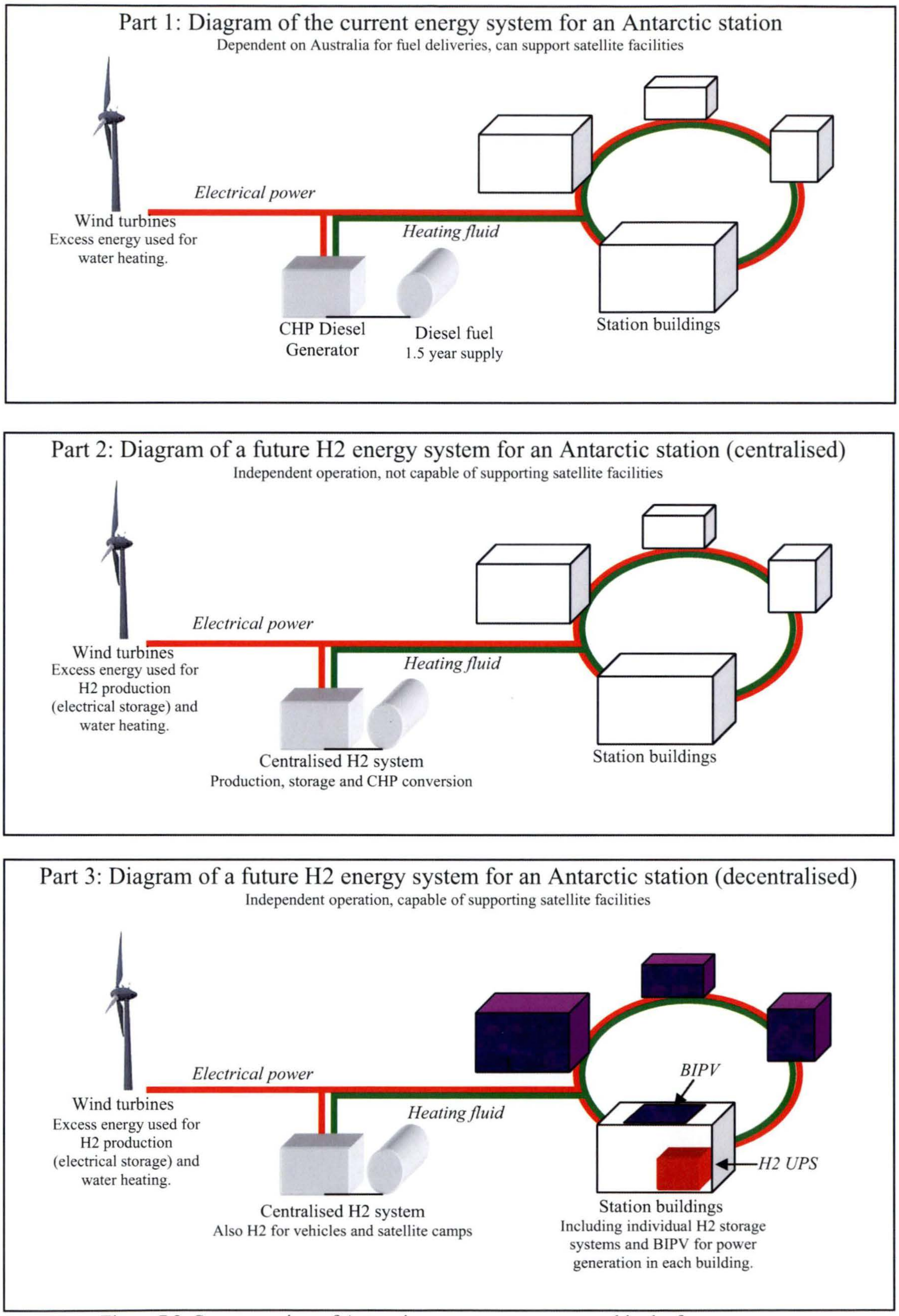

Figure 7.2: Summary view of Antarctic energy systems now and in the future.

7.1.2 Centralised energy storage for Antarctic communities

At present, the power systems of Antarctic stations such as Mawson are relatively centralised, including a single fuel storage system (diesel), two power generation systems (wind turbines and conventional powerhouse), and an electrical and heat energy distribution grid. Excess wind generation capacity is available but cannot be fully utilised without adequate energy storage.

The obvious initial application for hydrogen technologies at Antarctic stations is to serve as a storage mechanism for excess renewable energy resources that are currently dumped or converted into lower grade energy forms such as heat. Ideally, such a system would enable independence from imported fossil fuels for stationary power generation and heating within the station limits, subject to the energy demands of the station, availability of renewable energy resources, and the relative size of the energy generation and storage system.

The use of hydrogen energy technologies for the centralised storage of renewable energy could be achieved at Mawson Station via a number of routes due to the diverse nature of hydrogen-related technologies. An example would be the production of hydrogen through electrolysis of locally-generated water (melting from ice and snow), the storage of the hydrogen in appropriate pressurised tanks or metal hydride systems, and the conversion of the hydrogen to electricity via converted internal combustion engine (ICE) generators or fuel cells. Waste heat could be captured from the fuel cells or ICE generators and supplied to the reticulated heating system, as is currently done with waste heat from the DEG system. The successful commissioning of a comparable wind-hydrogen system (excluding the heat recovery component) on the Norwegian island of Utsira in 2004 has illustrated the technical viability of the concept [6].

As demonstrated by the Utsira island system, the implementation of a wind-hydrogen system by a remote Antarctic community would require careful consideration of the costs, performance parameters and proven reliability, and practicality of the various system components. The use of a wind-hydrogen system in Antarctica in the near future would conceivably favour ICE generators over fuel cells due to the cheaper cost of energy generation over the full life of the component, and the higher degree of access to maintenance and trained personnel that currently exists for ICEs. In contrast, fuel cells have issues with cost, service life, availability of trained operators and servicing agents, and more practical considerations for their use in a polar environment such as their operation in freezing temperatures. Ultimately fuel cells will offer advantages of higher energy conversion efficiency, silent operation and potentially reduced maintenance with their fewer moving parts.

Part 2 of Figure 7.2 illustrates the use of a centralised wind-H_2 system at an Antarctic station, achieving full independence from fossil fuel use. The system could utilise fuel cells and/or ICE generators for electricity production from hydrogen.

The advantage that this centralised wind-hydrogen energy system offers over the conventional solution is a further reduced dependence on fossil fuels and the potential environmental, economic and security of supply benefits that would result. This would be achieved by using a suitably sized and centralised hydrogen energy storage system to capture excess wind energy, effectively replacing the stored diesel energy component of the current system.

The system as described also has two important disadvantages. The first is the inability to provide transportable fuel to local vehicles and near-by field camps, potentially resulting in an impractical duplication of fuel handling activities and the continued use of fossil fuels for transport. Secondly, the system maintains the conventional design of a centralised energy supply system and does not access the potential efficiency and security-of-supply improvements that alternate energy system designs can provide. The characteristics of certain hydrogen energy technologies like fuel cells provide opportunities for innovative methods of supplying energy services to remote communities, such as through the development of decentralised energy storage systems. The following system seeks to address these disadvantages.

7.1.3 Decentralised energy storage systems for Antarctic communities

Hydrogen energy technologies enable the development of innovative energy systems that use multiple and distributed installations for power generation and energy storage operations to replace conventionally designed 'centralised' energy systems. In an Antarctic station context, such distributed energy systems could enhance the efficiency, versatility and reliability of a station's energy system without being constrained by the operational needs of conventional energy systems.

To achieve this, stand-alone hydrogen energy storage systems (e.g. electrolyser, storage, fuel cell) would be deployed around a station and connected to the existing electricity grid and potable water distribution system. These decentralised sub-systems would work in partnership with the centralised wind energy system to store excess energy within the station grid and to provide back-up generating capability in the event of power failure.

Primary applications for these decentralised energy storage and generation systems would be critical applications on the station including communications, medical and core living modules. In the event of disruption to the centralised power grid, the decentralised systems would ensure that critical applications remain serviced.

Where economically viable, additional decentralised systems could be deployed around the station grid to enable better management of the station's peak electrical load on the centralised generating infrastructure. For example, short-term energy demand peaks that would require the start-up of an additional generator or fuel cell in the centralised power plant could instead be met by drawing down on energy stored in a hydrogen system with an energy generation capacity more appropriate to the load. The decision to utilise the main powerhouse or a decentralised (small) system to meet the power demand would be made by the station's building management control system (BMCS). The BMCS would also be responsible for selecting the appropriate time for the localised storage systems to recharge their storage reservoirs, ideally during periods of excess wind energy. The continual maturation of the system would enable the BMCS to 'learn' the patterns of energy generation and use over time, providing opportunities for further optimisation of the energy system optimisation.

Ultimately, the primary power generation sources for the station grid will also be augmented beyond large-scale wind turbines with other renewable energy technologies such as building-integrated photovoltaic systems (BIPV). These technologies would enable a station to capture and utilise a variety of energy resources and produce power from numerous decentralised sources. The decentralised sources would integrate with the primary (centralised) generating systems to form a local-area power network that also includes centralised and point energy storage mechanisms based on hydrogen energy technologies. This decentralisation will enhance the security of energy supply for the station and reduce demand on the installation of primary and centralised power generation infrastructure such as wind turbines. In doing so, the net footprint and environmental impact of the station can be reduced. The recent development of new photovoltaic (PV) panels that produce comparable power outputs to conventional products with only ten percent of the material consumption and greater flexibility of application offer exciting prospects for a future of lower cost and more versatile PV products [7].

The energy systems of Antarctic stations must also consider the demands of other non-stationary activities associated with the station's operations, including local and regional transport systems, the fuel used by dependent satellite 'field' camps, and the energy used by individuals working around the station such as with portable devices (radios, scientific equipment etc). The following sections of this chapter examine how hydrogen technologies could be used to meet the energy demands of these operations. However, if these activities are shown to be viable, the hydrogen fuel required could be sourced from a permanent Antarctic station. This concept is examined briefly below.

Part 3 of Figure 7.2 illustrates how permanent Antarctic stations in the future can utilise a combination of decentralised primary energy generation (wind and BIPV) and energy storage systems (hydrogen) to enhance the stability of the station's energy system, and provide energy resources to the other energy users around the station.

The decentralised energy system described above offers a number of advantages when compared to the conventional or centralised hydrogen energy systems. The advantages include potentially greater security of supply due to the diversification of energy generation and storage systems; potential for increased system efficiency with closer matching of loads and energy supplies; and reduced demand for larger centralised energy systems and associated capital investments. From a practical perspective the system offers further advantages, including: opportunities for an incremental deployment of new technologies at appropriate levels of capital cost, operational experience, and technology availability; remote operation of all new energy system components (fuel cells, electrolysers) to optimise the system performance; and the potential to construct new stations from wholly modularised station buildings that include decentralised energy system components, minimising the need for centralised energy systems.

The principal disadvantage of the decentralised system is the larger number of components. This could lead to higher capital costs and increased maintenance, or simply provide more opportunities for operational faults. This second factor is of considerable importance for activities in the harsh and unforgiving Antarctic environment, where the reliable operation of energy systems is critical to human life.

7.1.4 Generation of transportable fuel to meet local and remote energy demands

Permanent stations serve as resource hubs for a range of energy-consuming activities in the region. The potential hydrogen fuel needs of these activities could be met with hydrogen specifically produced from components in the de-centralised energy systems of Antarctic stations. For example, an "H2 refuelling" facility could be developed on a modular basis with all necessary hydrogen production, storage, distribution and balance of plant equipment included in prefabricated units and coupled to the existing power and water circuits in a station's site services ring. Energy for hydrogen production could be sourced from BIPV panels mounted on the refuelling facility and/or from excess energy within the station system (e.g. from centralised wind turbines), with the buildings energy management and control system dictating the priority for energy routing to the refueller.

Refuelling systems that follow the basic principles of this concept are already commercially available and could be adapted for deployment to Antarctic operations. Following a modular format, perhaps based on the footprint of the C-sized shipping containers that are used in all Antarctic operations, would enable rapid deployment of the facility to appropriate locations. The facility would also have a minimal environmental footprint and be well suited to expansion to meet growing demand or for re-allocation to alternate sites.

7.1.5 Transition pathways for hydrogen implementation at Antarctic stations

Permanent Antarctic stations are generally substantial and complex facilities and Antarctic communities could be expected to be particularly conservative with regards to the introduction of an innovative energy technology into these important facilities. Consequently, a single-step conversion of an existing Antarctic station's energy system into an independent renewable and hydrogen energy system, such as one based on the concepts examined above, is viewed as a practical impossibility. Discussions with senior operations personnel with the Australian, Norwegian, Swedish and British Antarctic communities have confirmed this view. The stations represent large capital investments, play key roles in the entire spectrum of operations on the Antarctic continent and so cannot be easily decommissioned for any period of time, and have considerable operational and cultural 'momentum' in fulfilling their functions. The technical and social changes that would be required to complete a single-step transition would result in extremes of risk, financial investment and cultural and operational disruption that would not be accepted by the community.

Multi-step transition strategies must therefore be developed if Antarctic stations are to leverage the benefits of hydrogen energy technologies. Recommended elements of a transition strategy for the adoption of hydrogen energy systems by permanent Antarctic stations, based on the concepts developed for Mawson Station, include:

1. Reap the most from conventional and new energy technologies through accurate consideration of their relative advantages and disadvantages and appropriateness to the operations being considered.

2. Accept that fossil fuels will be around for a while to come, and use this to advantage by developing hybrid energy systems that include fossil fuels.
3. Use renewable energy to address issues of exposure to fuel costs, environmental impacts, energy security etc, without compromising the operational capability of the station by over-aggressive adoption of independent energy systems.
4. Use existing assets and operational experience effectively.
5. Recognise that diesel electric generators (DEGS) are a highly proven and cost-effective means of providing energy at Antarctic stations and do offer advantages over innovative technologies for many applications at this time. The existing investment in capital equipment and support infrastructure for these facilities could be effectively used, for example, as standby (emergency) systems to back up more sustainable energy systems.
6. Develop 'experience by doing' with hydrogen systems in efficient ways, such as through collaboration with other Antarctic programs or communities in remote regions who have similar interests (e.g. Arctic communities).
7. Target priority or high-opportunity applications first
8. Be prepared for opportunities that create favourable conditions to implement changes. For example, the retirement of existing assets, developments in the hydrogen technology field or reductions in prices, changes to operational needs of community, collaboration opportunities with other communities or technology developers etc.

A more detailed transition strategy for the introduction of hydrogen energy technologies into an existing permanent Antarctic station has been developed from this work, and is presented in Chapter 11.

Antarctic stations commissioned in the future may be able to begin with wholly independent energy systems based on renewable energy generation and hydrogen energy storage systems, but existing stations will have to take it one step at a time in their adoption of alternative energy technologies.

7.1.6 Conclusions for Hydrogen Use in Permanent Stations:

A range of options exist for the introduction of hydrogen technologies into stations, with numerous advantages and disadvantages for each approach.

A conventional approach to the use of hydrogen technologies in Antarctic operations would be for the partial or full replacement of the existing centralised diesel power systems with a comparable centralised system that utilised energy produced from a hydrogen storage system. The hydrogen would be generated using centralised renewable energy generation resources, such as the wind turbines at Mawson Station. The technical viability of developing a full wind-hydrogen system for Mawson Station will be evaluated in this research through computer modelling of the station's energy demands in Chapter 8, but the concept is supported by the practical development of comparable systems such as Utsira Island in Norway [6]. The technical and social challenges associated with developing such systems are evaluated in Chapter 9.

Practical considerations suggest that the best approach for communities would be to begin with growth in the penetration of renewables (wind, as is being done now), the introduction of small-scale use of conventional and/or novel hydrogen storage technologies to maximise benefit from turbines and to reduce demand on fossil fuels while maximising use of existing infrastructure and developing expertise with hydrogen products. This will reduce the need for diesel delivery (also other benefits), while using DEGS for low cost variability storage (and potentially to address heat issues). Outcomes from related projects such as the West Nordic project support this as an effective strategy to achieve cost-effective reductions in the communities that are most sensitive to diesel fuel price fluctuations [8]. The suitability of hydrogen technologies for such an iterative decentralised approach is appealing.

7.2 Temporary and small-scale research camps – Antarctic field camps

The scientists who travel the substantial distances necessary to carry out research in the Antarctic environment have interests in regions all over the large continent. However, the permanent research stations that have been established provide convenient access to only small portions of the region. As a result, a variety of temporary and/or mobile field 'camps' are established in Antarctica each year to enable scientific research to be conducted in remote regions that are not adequately accessible from the permanent stations. These field camps are supported by the permanent stations for their fuel, food, and equipment, and planned or unplanned (emergency) transport needs. The camps are deployed by land, sea or air transport, including the delivery of fuel to meet their stationary energy demands and operation of vehicles at and out of the camp.

As with all activities in Antarctica, environmental impact considerations are paramount in all operations. In field environments, impacts can be generated through waste disposal, fuel spills during storage or transfer, particulate and CO2 emissions from power generation, and noise emissions from human activities. Field camps can operate at specific sites for periods of time ranging from a few weeks over a single season, to multiple seasons spent at the same site or semi-permanent facilities that are used for over a decade. Most camps are used only in the summer season as the facilities are inadequate to support the needs of residents over winter. The logistical burden of deploying field camps is highly dependent on the location, activities and duration of the field expedition, including the amount of food, equipment, fuel, and personnel that need to be transported to remote locations. Field camps also often require on-going support through a summer season, such as for the delivery of fuel for power generation and replacement or repair of faulty equipment.

The energy demands of field camps can range from the operation of simple lighting, communications, cooking, and research equipment and personal devices (radios etc) to the support of energy-intensive equipment needed for more substantial in-field analysis. Examples include projects that require electrical heating and water production. The energy demands of camps can also include local vehicle use (quads, ski-doos) and regional aircraft operations. Energy needs currently at field camps are currently met with delivered fossil fuels (diesel, LPG, gasoline) in ICE generators, with small-scale renewables (wind, PV etc.), or combinations. Batteries are charged from generator sets or renewable energy resources, such as with the remote area power system (RAPS) developed for Macquarie Island shown in Figure 7.3.

Figure 7.3: Macquarie Island RAPS system developed by the AAD .

7.2.1 Case Study - Bechervaise Island, remote field camp

Beche (Bechervaise) Island is a small-scale research facility (5+ personnel) that operates specifically for the support of a science program and only operates during summer seasons on the Antarctic coast. The facility is semi-permanent in nature, and has close support from a nearby permanent station (Mawson). Figure 7.4 depicts facilities on the island and the distance between the island and Mawson Station. Energy demands at the facility are low, and are predominantly met using renewable energy resources. When required, stored energy resources supplied from the nearby station are used to supplement renewable energy systems. Personnel regularly return to the station, eliminating the need for substantial ablutions and waste disposal infrastructure.

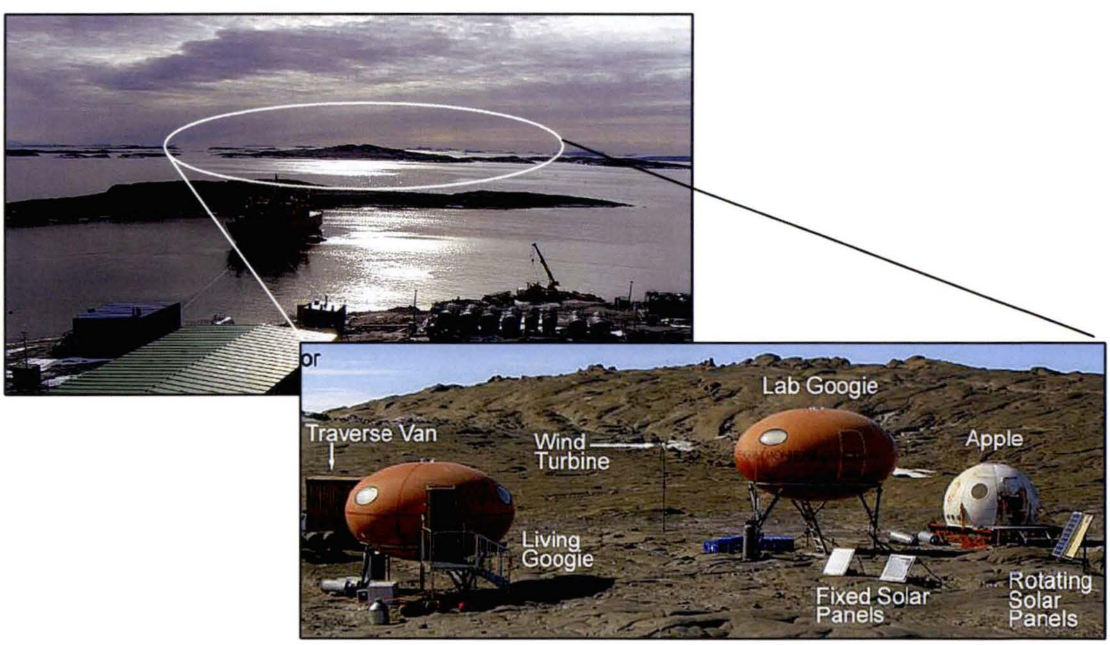

Figure 7.4: Bechervaise Island field camp, viewed from Mawson Station.

The facility currently operated at Bechervaise Island includes a number of different sub-systems and key activities, as outlined in Figure 7.5. Although all of these activities are critical to the successful operation of the research program at Beche, an accurate and worthwhile investigation of the energy supply systems for the entire operation is best achieved by separately reviewing each of the individual sub-systems.

Consequently, the Beche Island Energy Use case study will focus on the "Beche Is. Field Camp System" selection outlined in Figure 7.5, which covers the semi-permanent living and working facilities for the small population of researchers and support personnel on the island. The "Remote Comms System", "Temporary Hide System" and "Auto Equipment System" are not considered, but many of the outcomes from the study can be applied to these applications.

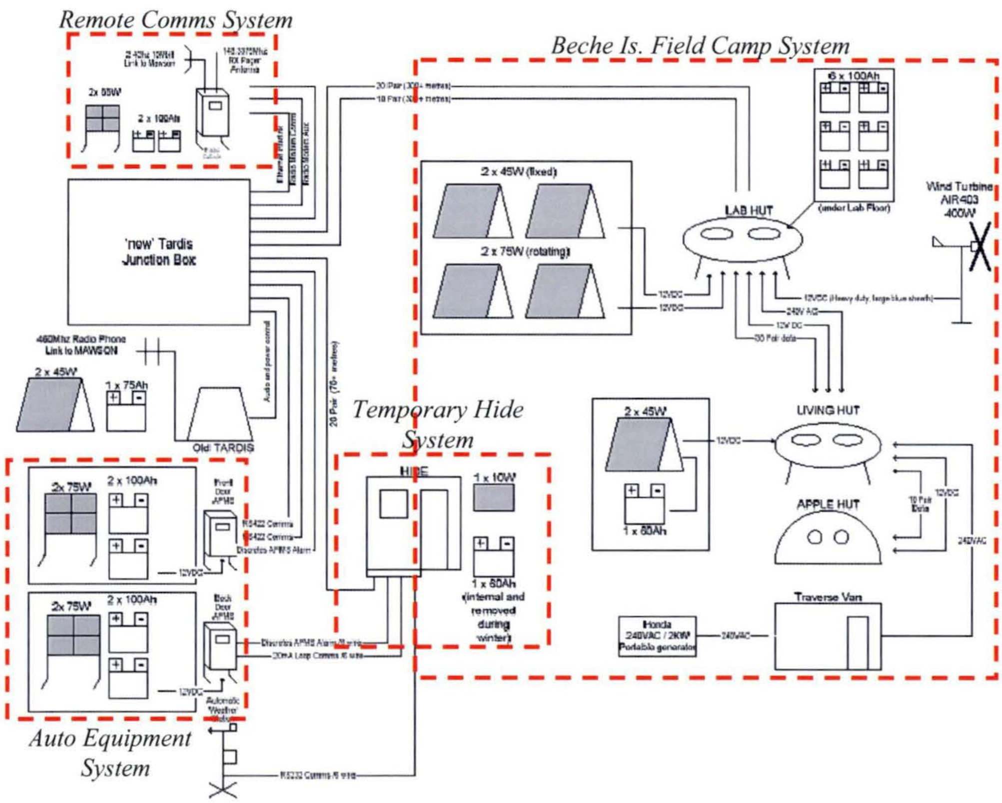

Figure 7.5: Diagram of comprehensive Beche Island infrastructure and energy supply systems. Source: Kym Newbery, AAD.

The Beche Island field camp facility is composed of a number of items of fixed infrastructure and a variety of energy supply systems designed to meet the varying power demands of the camp. These include wind and solar 12 VDC power generation systems, a petrol generator 240 VAC power system, and an LPG gas heating and cooking systems.

The main components of the field camp, as illustrated in Figure 7.6, include:

1. *Lab Module (Googie)* – main work area for the camp, providing space for equipment use and research work via laptop computers. Includes network, lighting, 12 VDC power, mains power (240 VAC) for equipment, and telephone connections.
2. *Sleeping Module (Apple Hut)* – mainly sleeping area. Includes network, 12 VDC for lighting and telephone connections.

3. *Living Module (Googie)* – sleeping and eating/living area. Includes 12 VDC power for lighting, cd/radio, computers and network connections. Mains power for specific activities such as bread making and microwave oven.
4. *Storage Module (Traverse Van)* – mainly for storing water, equipment and the storage and operation of a 240 VAC generator.
5. *Toilet Module* – enclosed toilet facilities with bagged waste disposed at Mawson.
6. *External Science Activities* – activities conducted around the island are also supported from the base camp, including charging of batteries for mobile devices or powering 240 VAC equipment.

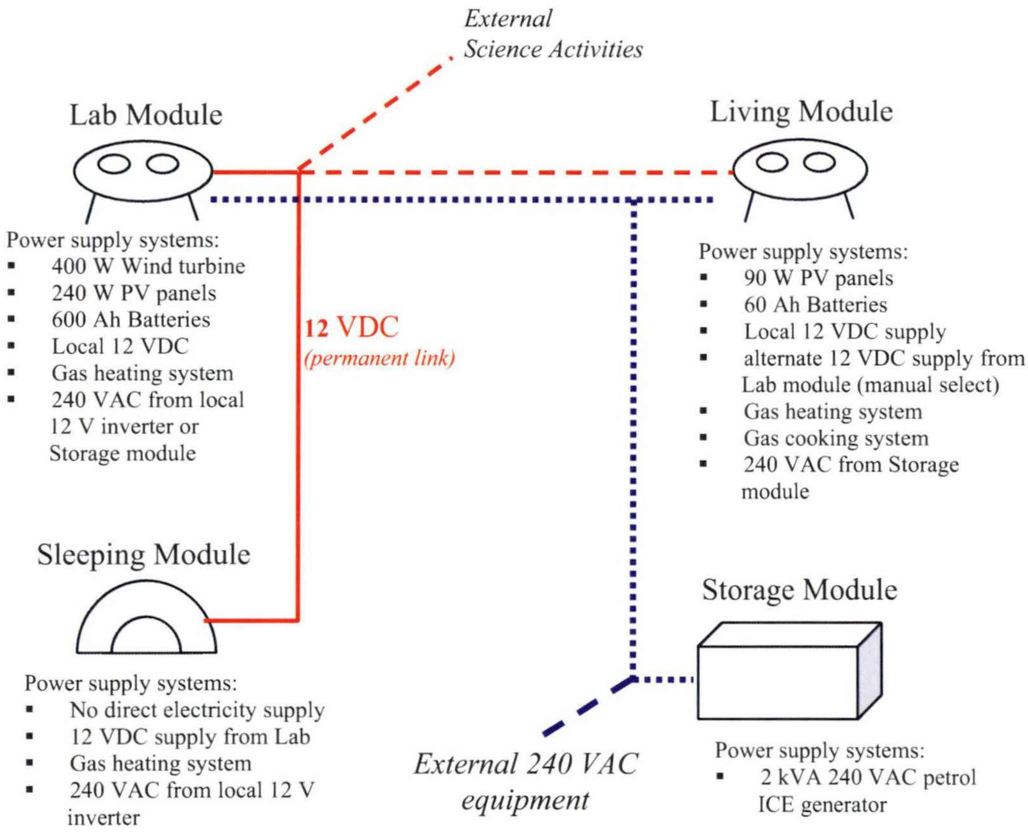

Figure 7.6: Main components of the Beche Island field camp and energy supply systems.

The energy supply system first illustrated in Figure 7.5 is further described below, and outlined in Figure 7.7:

1. 12 V DC power is used to meet the bulk of the electrical power demands in the field camp, and solar panels with battery storage form the foundation of the electrical supply system. A wind turbine contributes additional power when used, but concerns about noise and reliability (and high wind speeds) restrict its use.
2. When necessary, limited 240 VAC power (up to 100 W) is converted from the 12 VDC supplies, such as for laptop operation. For larger 240 VAC demands (microwave, breadmaker, other equipment), the 2 kVA generator is started and power supplied from the Storage module (Traverse Van).

3. The Lab module and Living module each have separate 12 V power systems, although 12 V DC power from the Lab module can be routed to the Living module (Googie) if required. This requires manual operation of a switch, and isolates one of the two systems. The 12 VDC power link is uni-direction Lab-to-Living module. 12 VDC power is constantly routed to the Sleeping module (Apple) from the Lab module, and the Sleeping module has no independent power supply.
4. Heating is provided using LPG gas heaters, with separate systems in each of the living, lab and sleeping modules. No heating is supplied in the storage module.
5. No passive solar heating is used.
6. Cooking is undertaken using LPG gas cook tops and ovens, and the 240 VAC microwave and bread maker see limited but daily service.

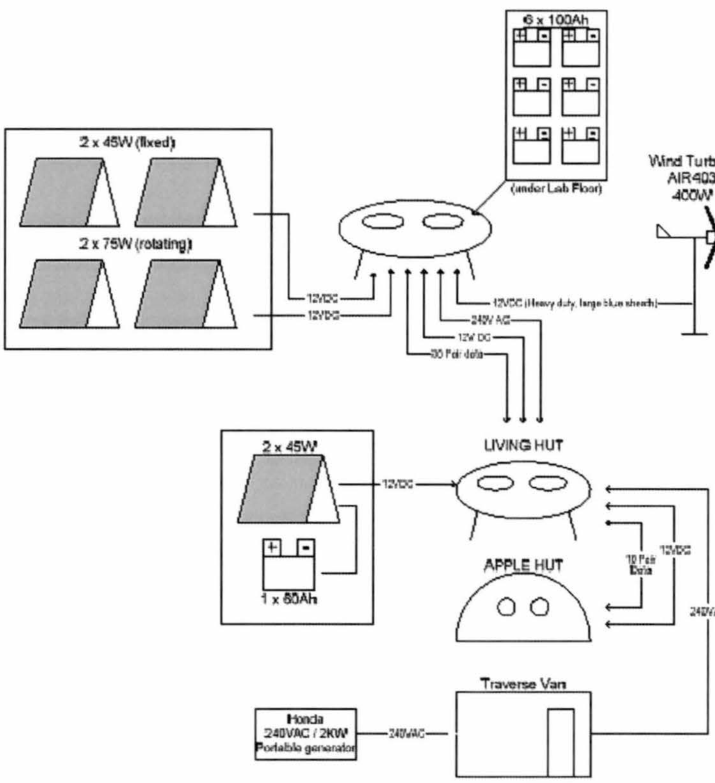

Figure 7.7: Diagram of the Beche Island field camp energy supply systems.
Source: Kym Newbery, AAD.

The inputs of the Beche Island field camp system include sun light, wind, potable water, food, personnel, petrol, LPG fuel, and other equipment. The outputs of the Beche Island field camp system include waste water, grey water, scientific data, communications, heat, combustion emissions, fuel spills, damaged/used equipment and general waste.

The potential roles of hydrogen technologies at Beche Island were identified after extensive discussions with the energy system design, installation and maintenance personnel (Kym Newbery at the AAD) in November 2003.

The Beche island infrastructure is fairly mature, and requires little development –

however, there are opportunities to improve some of the systems that currently operate. Beche is also illustrative of a variety of 'generic' Antarctic field camps, particularly given the dual environmental circumstances of being ice-bound for part of the year and water-bound for another. Consequently the system design and user parameters of the Beche system can serve as a foundation for a variety of energy use situations. Using the Beche technical system, different activity and environment profiles, user characteristics, and weather data sets could be used to simulate other energy supply scenarios. The Beche system could also be used to determine if a purely 240 VAC system running on H2 could operate the system, and what the fuel capacity would be. Even in modeling just the Beche scenario, a number of operational 'styles' will need to be considered, which will reflect the potential styles of other field camps and research activities. Such styles may include: a lot of internal lab work on computers, with 240 VAC equipment; a lot of outside work requiring little energy use in the modules; outside work requiring recharging of equipment from the modules; poor weather conditions where power demand rises and the input of renewable energy drops, etc.

The role of the Beche Island facility is to study long-term impacts of humans on a penguin population. The biggest upset to the penguins and other wildlife in the vicinity, therefore, is from the handling of humans during testing programs, including invasive and direct handling of the birds. Impacts from the camp have been considered, and are believed to be minimal (but still greater than zero impact). Issues such as noise emissions from the generator are not considered a problem. Consequently, the exchange of power generation equipment for the facility will not be overly driven by impacts on the system by the present equipment. However, issues such as fuel spills of petrol are a concern.

A number of aspects of the energy system were identified through discussions with the AAD as needing or benefitting from improved performance. They included:

1. Boosting the current performance of the energy supply system for the communications equipment (radio modem), although this is not part of the Beche Field Camp scenario. The current PV-battery system is suspected to be inadequate and a small auxiliary FC could provide back-up power. The radio modem tower is a critical, but currently weak, link in the Beche-Mawson communications set-up. A small FC running on H2 or methanol that required refueling every two weeks, or ideally once a season, would be a great advantage – this sort of system would serve as a good model for another scenario.

2. The current energy system of the living module is not adequate to run laptops etc for prolonged periods of time – greater battery capacity and PV input is required. With the advent of DVD players, MP3s, email, web surfing and chatting, etc and the growth of the laptop as a multi-functional device, these traditional 'tools' are seeing greater use in the living module than originally anticipated. There are two possible solutions to this – allow users to open the link between the lab and living modules and use the power from the lab module when required. Excess capacity is currently available in the lab module to allow this, but the option is isolated after the summer season to prevent other (less informed) users draining the batteries of the lab module. Alternatively, users could plug laptops into the 240 VAC system. This may result in prolonged use and trickle-charging of the laptop, thereby depleting the finite 240

VAC H2 supply. Consequently, (as discussed below), users should focus on operating within the constraints of the 12 V system and only use the 240 VAC system for specific tasks. Computer modelling could be done to determine the impact of operating one laptop in the living module permanently on 240 VAC.

3. Enhance the usability of the current 240 VAC system – this could be achieved by providing a system that offers "instant on-off" operation and does not require users to go outside (particularly in bad weather) to set-up and refuel the system. At present, the generator must be deliberately refueled, started and operated for the specific 240 VAC tasks. This takes time, is a minor distraction to activities, can result in fuel spills, creates irritating noise, and is not seamless. An on-demand fuel cell system that could directly replace the existing generator would be an ideal test for a hydrogen-based energy solution for 240 VAC power.

A recommended approach to address this issue is the use of the existing 240 VAC distribution system to evaluate the performance of an H2-FC which provides power for specific 240 VAC tasks, operating on-demand. The current energy demands of such tasks are known, and a culture has been established to maximize the use of renewable 12V power. Exchanging the generator with a FC would also result in minimal impact on the current operating system. The FC could be stored in the traverse van, where the generator is stored for operation outside. The FC could operate at an 'idle' setting inside the van over the summer and meeting demand as required. The internal operation would also provide temperature balance in the van.

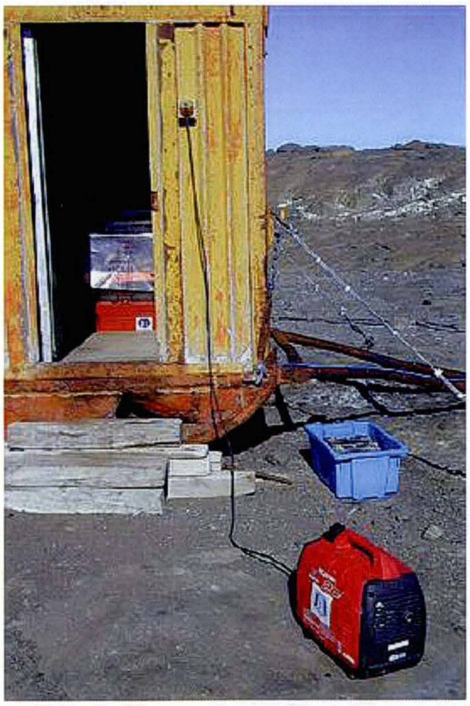

Figure 7.8: Honda 240VAC generator providing power to the Beche Island system via the Traverse Van connection point. Image courtesy of Kym Newbery, AAD

The replacement of the generator with the fuel cell would provide an opportunity to maximize the efficiency of the H2 use by operating the FC inside the living module, capturing the waste heat etc. However, a number of factors suggest that the FC be operated in the storage van. These include: the period of operation of the FC will be quite small based on the existing use of the gen-set, hence the amount of useful heat produced by the FC will be minimal. The system changes required to allow use of the FC in the lab module may not be warranted based on the amount of useful heat it will produce. Using the FC in the traverse van will require minimal changes to the current system, and serve to illustrate the first point that H2-FC can replace diesel generator. Also, any operator fears about living/working next to a FC will be averted by separating users from the FC. This issue can be tackled in the future. During the initial period of testing, the generator will be available at the camp, and if the FC fails or H2 supplies are depleted, the generator can be easily re-connected to the grid.

From an initial demonstration perspective, the current field camp is designed for two fully separate power systems, and works very well. This should not be disrupted, and should be learnt from. Low power systems are safe and use generic 12 V components or adaptors for 240 VAC devices (under 30 W). This power system is designed for such loads to protect users and equipment. The heavy load system is designed for specific high power loads, again better protecting users and equipment. Consequently, any H2-FC system should follow these guidelines.

Operating the FC in the traverse van may require improved air intake for the FC. Some concerns exist about the impact of stored water reserves in the van providing a high thermal mass that tends to freeze. Options such as passive solar heating, improved insulation, or specific insulation of the FC and or water, could reduce the likelihood of the fuel cell working at too low a temperature.

The FC provides an advantage of greater electrical efficiency, potentially requiring less fuel consumption etc, and then the additional benefits of internal heating etc. However, the 'real-life' access issues of somewhere like Beche become a concern if refueling has to be undertaken multiple times during a summer season. Handling gas bottles in and out of an IRB is difficult and unsafe. In such circumstances, 20L fuel containers (petrol or methanol) are more preferred.

The need to demonstrate renewable H2 production and use via fuel cells, and potential clashes with more situation-sensible options for Beche was discussed. The purpose of modeling (technical) is to identify optimized solutions, and the non-techneical evaluation takes into account other needs and constraints. The viability of hydrogen, fuel cells, methanol and other such solutions is not yet known, but a number of constraints exist. The real situation may be that a single H2 tank system will not run the camp 240 VAC power for the entire summer off a FC, and refueling via IRB is not possible. In reality, the generator or a methanol FC may be a better solution for Beche. However, the greater impact of demonstrating the H2-FC system for even part of the summer will include awareness of and understanding and skills development with renewable hydrogen energy technologies. This stimulation may enable consideration of specific solutions such as methanol for Beche in the future, and subsequent use in the other energy systems used at Beche Island for science programs.

A potential difficulty for the H2 system is long-term storage out in the field, either because of the high capital cost of the storage systems, potential for damage in the weather, or slow loss of fuel content. Conversely, fossil fuels can be left for years in the field without serious loss of performance. This raises the question: should field programs of the future rely on indiscriminately available fuel dumps, or each should be fully independent and result in no long-term impact on the region, including leaving surplus fuel for future expeditions? For somewhere more semi-permanent like Beche where a single 44-gallon drum of fuel lasts a few seasons, can a hydrogen system compete in terms of convenience of deployment and long-term storage?

The fact that the current 240 VAC operation requires such fiddly operation of the generator acts as a natural restriction to its use. Providing a system that requires little or no user input does provide an opportunity for energy consumption to grow unmanaged to meet demand, particularly if users opt to consume 240 VAC power rather than use the existing 12 VDC network. A number of strategies could be proposed, including dead-man (time delay) switches for the 240 VAC system; or more appropriately – education and information on user strategies and the management of the energy supply system. It is understood that the summer science programs tend to display a better understanding of the operating philosophy and constraints of the current system, and this knowledge is not shared by more casual visitors from Mawson Station in the winter. Hence, the summer users have more privileges. The overall solution for the energy supply methodology is to promote the use whenever possible of the replenishing 12V power, including to power low-power 240 VAC appliances via inverters. The manual transfer switch between the lab and living modules (12 VAC) allows this to happen at the moment for summer users. When specific 240 VAC power is required, or if the 12 VDC system is inadequate, users would be able to consume power from the 240 VAC H2-FC system. Users must be educated to manage their own power usage, and analogies to car fuel tanks and operations are made. Essentially, the 12 VDC system can be replenished over the summer, so users can alter their behaviour based on the varying capacity of the system. The 12 VDC system has virtually infinite capacity as it can be replenished with local renewable resources, but it can only provide a certain amount of power over a set period time if the rate of energy consumption is higher than the recharge rate. Alternatively, the 240 VAC system has a finite capacity and finite output – much akin to a tank of fuel in a car – depending on how the car is driven will influence how long it will operate. To facilitate responsible use of the system, users should be educated about the simple operating ethos, and a method developed to provide users with real-time feedback on the performance of the 12 VDC and 240 VAC systems.

An example of feedback systems would include:

1. A real-time indication of the depth of discharge (DOD) for the battery banks of each 12 V system – this represents the fuel tanks of the 12 V system. The indicator should reflected on a scale from 1-100% the relative capacity of the top 30% of the battery bank capacities (i.e. the maximum possible discharge of the battery is 70%). With this information, users can determine if non-critical equipment should be operated or not, or an alternative power supply used. Alternative power supplies include the 240 VAC system for all modules on the base, or (for the living module) opening the 12 VDC link to the lab module.
2. An indication of the on-going capacity of the 240 VAC H2 system – expressed in the same way as a car fuel tank as "Empty" to "Full". Ideally the system would also determine at what point in the future (date or total hours), based on the average consumption to date, the system would reach empty (as per car trip computers). Users would be able to manage their own 240 VAC energy use and determine if it is sensible to support non-critical activities with the H_2 system.
3. All monitors should illustrate real-time values and recent history to illustrate rates of consumption and changes in power usage.
4. As the 12 VDC and 240 VAC system have maximum output rates, real-time monitors should also indicate the on-going power demand on the system in explicit demand (Watts) and as a percentage of maximum capacity. Some systems, including the fuel cell, can endure over-capacity operation for limited periods of time, and a warning alarm can be included into the display to enable 'controlled' over-rated-capacity operation. As a suggestion, an audio alarm should sound if the FC is over 100% capacity and within the maximum possible

capacity (say, 150%) but continue operation (alarm must be stopped manually). The system will then operate for the allowable time period of over-capacity operation (eg: 10 minutes), at which point a further alarm will sound, and 60 seconds later the system will shut down the power demand from that module to reduce power below the peak level.

Creating a culture of effective energy/resource management is a key element to the introduction of more self-sufficient and lower impact operations as they are more sophisticated that forgiving fossil-fuel based systems but provide more opportunities. Creating this culture requires explanation of the reasons why, and providing the users with the information necessary to manage their energy and resource use. There are examples of such efforts being achieved within the Australian Antarctic community already.

7.2.2 Roles of hydrogen energy technologies in Antarctic field camps

Based on the outcomes of the Beche Island case study, and broader consideration of the supply of energy services to remote field camps, the roles that hydrogen energy technologies may play in the operation of field facilities in remote locations of Antarctica include:

Stand-alone energy systems - hydrogen energy technologies could form the core energy storage component of stand-alone power systems for remote areas, enabling more effective use of renewable energy resources (wind, solar etc) to meet stationary and mobile power demands.

At Beche Island, for example, hydrogen production, storage and conversion technologies (and clean water storage) could be installed on the island to replace or augment the operation of the batteries in storing excess renewable energy.

Supported energy systems – externally produced hydrogen 'fuel' could be transported to a remote site and used to meet stationary power demands when local renewable energy resources are insufficient or their deployment is impractical, and/or to meet the fuel and energy demands of local vehicles and mobile energy consuming activities.

When used in this manner, the hydrogen would replace the role of conventional fossil fuels, offering protection of the local environment and other benefits associated with use of a sustainable fuel produced in the region (at Mawson Station, for example) rather than imported from external markets.

Emergency energy systems - All field facilities require emergency equipment packs to enable a rapid response to issues in the area, potentially including the destruction of a field camp and all associated equipment. Such packs provide emergency accommodation/shelter, provision of food, water and heat, facilities to provide emergency medical care (including temperature-sensitive drugs such as adrenalin), and equipment needed for navigation and communication with other parties. Emergency energy systems that used hydrogen energy technologies could improve the performance of such systems by operating in active and passive capacities – passive energy systems provide the stored energy required for the emergency packs to operate on-demand when required; active systems could also use hydrogen energy technologies to enable remote monitoring of the status of an emergency pack, to maintain controlled temperatures in medicine/drug cabinets, or to provide an active locator beacon for search parties. The active and passive systems could each use energy systems that are dependent on imported hydrogen supplies, or could also integrate renewable energy systems to meet energy demands where possible. With the expansion in the use of fixed and rotary wing aircraft to and around the Antarctic continent by national programs including Australia, the role of emergency shelters and equipment packs will similarly expand and conventional energy technologies are not well positioned to meet that need in the Antarctic environment.

Automated research and operational equipment – a variety of automated electrical devices and systems are used for research and operational tasks in Antarctica, including remote communications repeaters, weather stations, autonomous stationary research programs, and tagging of wildlife. Hydrogen energy technologies can be used to meet the small but long-term power demands of such systems.
The advantages of using hydrogen technologies at field camps are proposed to include:

1. Enable increased use of renewable energy resources so that facilities are more self-sufficient and have reduced environmental impacts.
2. The reduced usage of fossil fuels also reduces the logistical burden (and cost) of transporting fossil fuels to remote sites, and reduces the likelihood of environmental or occupational impacts from refueling and storing fuels.
3. The decentralisation of energy systems results in more efficient use of power over the whole system as the capacity of energy generators can be more closely matched to the demand.
4. Technologies such as fuel cells can operate silently, reducing noise pollution for human and 'local' residents.
5. The combined heat and power (CHP) capability of fuel cells provides opportunity for improved occupant comfort and energy efficiency through heating of accommodation and working spaces at the field camps.
6. Hydrogen technologies can be more practical for deployment to remote sites as they do not require on-going management such as charging of batteries or changing of air filters.

The potential disadvantages of using hydrogen technologies in field camps include:

1. Potential for the camps to run out of hydrogen because knowledge of the renewable energy resources in specific locations is poor and the demand on the hydrogen system may be greater than expected. This could be addressed through the use of a system that is capable of generating hydrogen but is deployed with a full tank of hydrogen.
2. The weights and volumes of hydrogen systems for full deployment could exceed those of conventional fossil fuel systems for some applications, generating greater logistical deployment burden.
3. The transfer of large volumes of hydrogen by aircraft in Antarctica may not be possible or preferred by personnel and regulators.

7.2.3 From theory to reality – a demonstration hydrogen system for Beche Island

As a consequence of this research project, many of the principles outlined in this case study will be tested via the deployment of a small-scale fuel cell to Bechevaise Island as a core component of the Mawson hydrogen demonstration project.

Hydrogen will be produced at the nearby Mawson Station via electrolysis from excess wind energy. The hydrogen will then be stored in two relatively light weight composite tanks, transported to the island, and used to replace the conventional fossil fuel energy systems for heating and power generation. A small (1-2 kW) PEM fuel cell will replace the current petrol generator and a switchable hydrogen- or LPG-fuelled stove will replace the existing LPG-only oven.

The tanks have physical volumes of 150 L and will be charged with hydrogen gas to pressures of 3000 psi – this is equivalent to approximately 30 600 L hydrogen gas as standard conditions (0 deg C, 1 atm). The LPG-H2 oven has been purchased, with development undertaken by a small Tasmanian business.

Figure 7.9 below presents the AAD's conceptual view of the full "Mawson Hydrogen Demonstration Project", with hydrogen production from excess wind energy at Mawson and the transfer via wheeled quad bike to a remote field camp (Beche Island) for use in generating electricity and supplying heat for cooking.

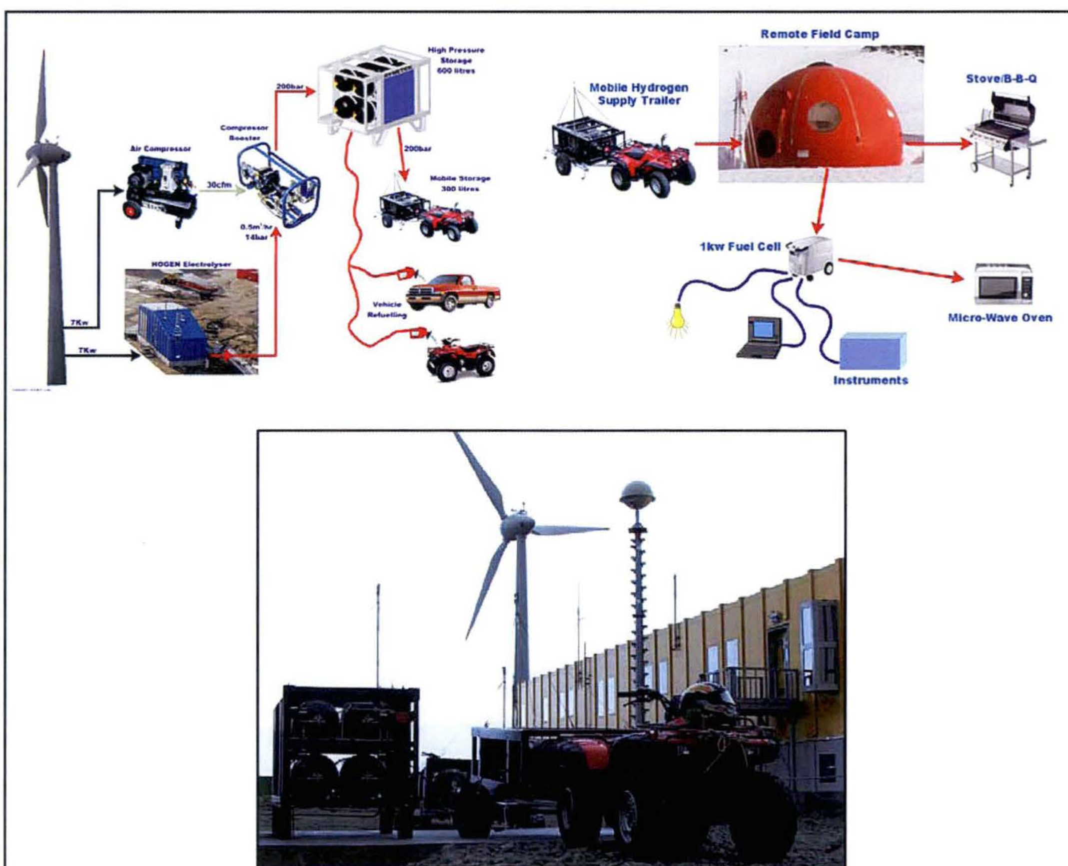

Figure 7.9: conceptual view of the Mawson hydrogen demonstration project, and practical reality of the wind turbine, hydrogen storage tanks, and vehicle trailer. Images courtesy of P. Magill, AAD.

Discussions with the AAD project engineer, Peter Magill, provided a number of relevant details about fuel cell selection and hydrogen use at the Island, including:

1. A 1.5 kW (rated power) fuel cell was being sought, but a 1-kW device would suffice, depending on what products emerged in early 2006. The ability of fuel cells to operate for short periods of time at levels above their rated power (peak power) supports this concept that a 1-kW fuel cell may be adequate to operate devices such as a bread maker with short-term power demands that exceed 1 kW.
2. Fuel consumption calculations are based upon 2 hours of cooking per day, and an average FC power output of 300 W (7.2 kWh/day), with Magill predicting the two hydrogen cylinders to last around seven days. A key outcome from the project will be to capture realistic measurements of energy demands and the performance of the energy system components.

Analysis of the energy demands of the Beche Island operations that were independently undertaken as part of this research project suggest that power demand for the fuel cell, if it is used to directly replace the existing petrol generator, should be significantly less than an average of 300 W. The known energy demands for the community indicate that the most consistent loads are for lighting of the lab module and the operation of laptop computers. These loads are currently met by the 12 V wind-solar-battery system, not the generator, and are below 300 W. As discussed above, in periods of poor weather when community members may be indoors (rather than out doing field work) and using their laptops for longer periods of time, energy demands will increase above the average level. Power generation from the renewable resources may also drop due to poor sunlight and extreme wind conditions. Therefore, the fuel cell system could be utilised under these circumstances to augment the basic 12 V system. At other times, only intermittent demands on the 240 VAC system total will result from the use of devices like the bread machine, microwave, and tools and laboratory devices. This usage could result in much less energy consumption than the average of 300 W predicted by Magill (say ~100 W or 2-3 kWh/day).

Data sourced for a commercially available PEM fuel cell product (VE 100 v3 MEU Military Version), as presented in Figure 7.10, provides some relevant details on the fuel consumption of such devices. The product has a 100 W (continuous) rating (and 200 W peak loading), so is not directly suitable for the 1000 Watt output required for Beche Island, but provides fuel consumption data that can be extrapolated for larger systems [9].

VE100 v3 MEU Millitary Version
(230v 50Hz AC and 13.8VDC)
Item number:542235 Price in August 2005: US **$9,120.00**
Sourced via: www.fuelcellstore.com

Figure 7.10: 100 Watt fuel cell available for application in harsh field environments.

Using the VE100 fuel consumption data as a basis for extrapolation, Magill's estimate of energy demand indicates that the hydrogen storage bottles sourced for

Beche Island should have a delivery life of 5.6 days, or approximately 11 days for the two bottles. This contrasts with the prediction stated above of 7 days for the two bottles, but the latter assessment includes use of hydrogen for cooking in a gas stove. Pointing's prediction of 2.5 kWh/day results in hydrogen supply of 15.7 days per bottle, or around 31 days (over one month) for the two bottles. This slower rate of fuel consumption would require roughly 3 refuelling operations for the facility for a summer season, a more manageable prospect than transporting a new set of bottles every week (12 refuelling operations in a season). As discussed, the demonstration project will provide a definitive means of determining both the energy demands on the hydrogen energy system and the subsequent refuelling schedule that would be required. However, the costs and complexities associated with deploying the hydrogen storage tanks provide obvious motivations to reduce energy demands on the fuel cell and stove and subsequent hydrogen consumption.

As the manufacturer specifies an operating temperature range of 5 °C to 40 °C, fuel consumption figures for these types of products may be higher in the Antarctic environment. Reasons for this include: the fuel cell may have to operate continuously to maintain a suitable temperature and the electrical conversion efficiency of the fuel cell stack may be reduced due to the greater loss of heat to the ambient environment. Operating a 1000-W fuel cell continuously with a standby power load of 25-30% would validate Magill's expectations of an average 300 W load for the cell. Alternative approaches to continuously operating the cell to maintain operating temperature could be devised so that the system could be shut down when not in active use. One possible solution is presented in Table 7.2.

The featured fuel cell also illustrates the maturation of these products, exhibiting a number of features that are sought by operators such as the AAD. They include:

1. Dual Output 230 VAC + 13.8 VDC, with other DC and AC outputs available; this feature is very compatible with the dual-voltage designs of systems such as Beche Island, and provides flexibility for using a range of devices in the field.
2. Self contained system requiring no additional control systems
3. Comparable in size to alternative products such as the existing Honda petrol generator, with approximate dimensions of 30 cm wide, 28 cm high, 19 cm deep; and approximate weight of 6 kg (13 lbs).
4. Battery and start up: automatically rechargeable and <10sec to full load
5. Noise emission: <35 dBA at 1 meter.
6. Operational hours before performance falls by 10%: 1500 hours
7. Built in fail safe reset, overload protection, and fuel usage indicator.
8. Appropriate certification and testing, including IP65 rating and CE Certification.
9. Operates on pure hydrogen (99.999%) with a supply pressure 0.4 PSI.
10. Unit is capable of continuously monitoring a 12 volt lead acid battery bank.
11. Support and Maintenance - Remote diagnostics available via integrated RS232 serial port. Optional connection through local VPN and TCP/IP link. Remotely upgradeable software via RS232 serial port - modem and dedicated line required. System Safety Management - The unit will automatically manage the system and warn on certain failure conditions. In the unlikely event that a hydrogen leak is detected, the unit will shut down. However, most other conditions will be managed in order to keep some power available whilst preventing the stack from damage. If the power level exceeds the normal loading for too long or exceeds the peak loading, a buzzer will sound indicating that the user should remove

some load or the unit will go into standby mode and disconnect the power outlet.

Innovative designs to operate a PEM fuel cell efficiently
in the harsh Antarctic environment

The low ambient temperatures of the Antarctic environment present a number of challenges to the use of technologies such as fuel cells due to the impact on start-up times, operating efficiency, and potential for damage to the system such as through the freezing of the water in the cell or exhaust stream. An obvious strategy to address these issues is to permanently operate fuel cells in low-load 'idle' modes, although this results in unproductive consumption of fuel. A theoretical alternative to this strategy is to mount the system in an enclosed and insulated 'environment' container.

Such a container would enable the operating features of the fuel cell to be used to the greatest advantage and enable the system to be effectively switched off when not required. A key component of the concept would be to utilise the waste heat from the fuel cell operation to preheat incoming air for the stack. This would reduce the cooling effects of the external air fed to the stack during operation (thereby improving efficiency) and also used to heat a reservoir of thermal mass within the insulated container to maintain temperatures above 0 °C.

With the thermal mass providing an appropriately warm environment, the fuel cell could be effectively turned off when not in active use without fear of damage or slow restart. A control system could monitor conditions within the container to ensure that the temperature did not fall below a minimum level, operating with low power demands from a rechargeable battery. If the monitor detects that temperatures within the container have dropped to a critical low level, the fuel cell would be activated by the controller to produce energy directly for the heating of the thermal mass within the container (and waste heat would also contribute). This 'pulse' of heat would enable the system to return to hibernation until user demand or the temperature trigger required further operation.

Such a system would provide other potential design opportunities, such as to use the moisture within the exhaust gas of the system to preheat and rehydrate the arid ambient air in Antarctica. This would reduce the chances of disrupting the relatively delicate humidity balance of the polymer membrane that forms the heart of the fuel cell stack. A battery storage system could also be included within the insulated container to instantly meet user energy demands while the fuel cell 'wakes' from inactivity (potentially a few seconds, depending on temperature) and to provide additional peak load capacity. The battery could be recharged by the fuel cell during operation (and during heat pulses triggered by the controller), and the thermal mass and insulation of the container would reduce the potential for the battery state of charge to decay from low temperature influences.

Table 7.2: Innovative designs to operate a PEM fuel cell efficiently in the harsh Antarctic environment.

7.2.4 Conclusions from Remote Field Camp Scenario

A diverse range of 'field camps' are used in Antarctic operations, from facilities that house a handful of people for a short summer season to longer term 'semi-permanent' operations. The development of new large stations with similar characteristics to field camps also increases the diversity of systems [10].

Hydrogen technologies have been shown to have a wide range of potential roles – as stand-alone energy systems; as supported systems that depend on hydrogen fuel produced at other locations (strengthening links between use of hydrogen at permanent stations and field camps); and as emergency energy services. The supply of power to automated research devices and operational equipment is also very relevant to field camps, and is considered in greater detail in the following energy use scenarios.

Within field camps, there are opportunities to use conventional technologies such as DEGS and burners, or novel technologies such as fuel cells, operating on hydrogen fuel. The use of hydrogen offers advantages and disadvantages over conventional solutions. As concerns about operations in sensitive environments or logistical expenses of delivering fuel increase, the viability of more expensive hydrogen technologies will increase.

The case study assesses the use of hydrogen in a supported system capacity at a field facility closely located to Mawson Station, with sensitivity issues associated with local wildlife colony. It illustrates that the existing system is well designed with separate 12V and 240V systems, but in need of enhancement. The design is well suited to the use of hydrogen in direct replacement role of conventional fossil fuel systems (240 V DEG and LPG burners). This would provide advantages of less noise, potential for automation, less fuel handling etc. There is also long-term potential for maximizing combined heat and power opportunities of FCs in small environments, but initial implementation efforts should focus on the "swap in-out" replacement of conventional systems. As the design of the energy system at Beche Island would enable hydrogen technologies to be introduced with minimal disruption to operations, this suggests that field camps are well suited for the initial evaluation and demonstration of hydrogen solutions; particularly facilities like Beche that are semi-permanent in nature and located close to permanent stations.

Beche Island could also be representative of many other field camp energy systems and styles of operation. As the field camp is forming the focus of the Mawson Hydrogen Demonstration Project based on these values, this provides a valuable opportunity to assess the validity of this analysis through real life tests.

7.3 Antarctic transport systems

Effective transport systems are essential to the safe and efficient execution of scientific research activities in the Antarctic region. As summarised in Table 7.3, a variety of transport systems and vehicles are used in Antarctic operations and hydrogen energy technologies can subsequently play valid roles in a number of areas.

Types of vehicles	1. Air, sea and land transport vehicles 2. Passenger transport, cargo transport, mobile research laboratories, utility and construction equipment, and multi-task vehicles. 3. Single occupant/operator vehicles or vehicles with multiple passengers and crew
Journey distances	1. Station and local area transport 2. Regional or intra-continental transport (100s of kilometres) 3. Inter-continental transport (1000s of kilometres)
Energy demands	1. Primary energy demands (mobility) a. Serving as the sole or primary power system b. Meeting only peak load capacity, operating in partnership with conventional generation technologies 2. Auxiliary energy demands (other than mobility)
Potential hydrogen fuel mix	1. H_2 as pure or unblended fuel 2. H_2 as fuel additive in conventional fuels (e.g. diesel)
Sources of hydrogen fuel	1. H_2 fuel supplied from an external sources (e.g. generated from renewable energy at a permanent station) 2. H_2 generated within the vehicle

Table 7.3: Elements of Antarctic transport systems and the roles of hydrogen energy.

Antarctic transport systems enable the long-distance transport of personnel and equipment to the remote continent, the distribution of personnel and equipment around the region such as to permanent sites (stations) or remote field camps, and include localised transport around permanent facilities or at remote locations. The types of vehicles subsequently employed cover a broad spectrum of marine, land and air craft ranging in capacity from single-occupant vehicles like four-wheeled motorcycles (quads) to relatively large ice-strengthened vessels. Examples of two common Antarctic vehicles are included in Figure 7.11– Hagglund oversnow vehicles and four wheeled 'quad bikes' or all terrain vehicles (ATVs).

Figure 7.11: common Antarctic transport vehicles – Hagglunds and quad wheeled motor bikes.

The role of vehicles in Antarctic operations often extends beyond the simple facility of travel, with vehicles pressed into additional services such as mobile accommodation and research platforms (caravans) or as mobile powerhouses to operate tools or research equipment in field locations. Due to the nature of the harsh Antarctic environment, vehicles must operate a variety of critical equipment items such as radar, communications, and navigation equipment. Consequently, the energy demands of Antarctic vehicles can be classified as *primary* (mobility) and *auxiliary* (other energy demands).

Antarctic vehicles are currently powered using a wide range of fossil fuels. These fuels vary between the different national programs, but common fuel mixes include: heavy or light bunker oils for ice-strengthened ships; low-wax diesel fuels (SAB for Australia) are common fuel for most land vehicles, particularly at the permanent stations; gasoline for small vehicles such inflatable boats and quad motorbikes; and aviation kerosene for helicopters and aircraft.

These conventional energy systems result in environmentally damaging fuel spills and emissions and are wholly dependent on external supplies of fuel and the subsequent deliveries to and around the continent.

7.3.1 Roles of hydrogen in Antarctic transport systems

The flexibility and versatility of hydrogen energy technologies will enable their application to the primary and auxiliary energy demands of Antarctic vehicles and complete transport systems. Examples of the ways in which hydrogen technologies could be used include:

Direct use of hydrogen as a fuel in the primary power system of a vehicle, with energy conversion achieved via internal combustion engines (ICE) or fuel cells. Other innovative vehicle energy technologies, such as hybrid electric drive trains, could also be used to enhance vehicle energy efficiency and performance. The General Motors hybrid vehicle system and auxiliary power unit developed for the COMBATT range of military vehicles provides an example of how this could be done [11]. Illustrated in Figure 7.12, the COMBATT truck includes a diesel electric drive train and hydrogen auxiliary power unit (APU) in the rear to operate electronics when the vehicle is stationary. The APU is charged using excess power from the engine when the vehicle is driving. Such technology could be transferred to similar vehicles such as the Hagglund oversnow vehicle used by Antarctic communities.

Hydrogen fuel could also be used directly in smaller vehicles (e.g. quad bikes), and this may be a simpler route to introducing the technologies into operations. The AAD has commissioned the University of Tasmania's School of Engineering to convert a quad bike to operate on pure hydrogen fuel in its existing combustion engine, based on this principle. Figure 7.12 below depicts the converted bike towing a trailer that also contains hydrogen fuel – the combined system enables clean fuel to be delivered to remote field sites using clean fuel. Storing sufficient quantities of hydrogen fuel is a potential issue with the use of hydrogen in this role, but relative advantages may emerge for remote operations if local vehicle fuels can be produced from local resources.

Figure 7.12: The GM COMBATT hybrid truck (left); and a hydrogen fuelled quad wheeled motorbike towing a hydrogen storage container for use at a remote field site (right).

Use of hydrogen as a fuel additive to conventional fossil fuels such as diesel, with the hydrogen produced at permanent stations in Antarctic from renewable resources. Blending of hydrogen into hydrogen carbon fuels reduces handling issues and storage challenges, while improving the environmental performance of the system (e.g. 10% by energy content contribution of hydrogen would reduce the environmental emissions). This technique could be used as a strategy to effectively increase the hydrogen production capacity at the stations without committing to reconfiguration of the transport fleet. The question of how it would be done on a practical basis, and whether it is worth the effort as opposed to simply switching to pure hydrogen must be considered. Research at UTAS and others considers the concept for RAPS, so if the station were also to run existing plant on a D90H10 mix (90% diesel, 10% hydrogen), this could be worth developing for transport vehicles (achieving a total 10% reduction in fossil fuel use) [12].

Hydrogen energy systems serving as power supplies for *periods of peak load in partnership with conventional primary power systems* (similar in concept to a turbo-charging function).

Independent hydrogen energy systems *meeting auxiliary energy demands when the primary power system is shut down* (auxiliary power units, APU). The hydrogen system may be fuelled with hydrogen from external supplies, or the APU may include a 'regenerative' hydrogen system capable of producing hydrogen from excess energy that is sourced from the primary power plant during travel. The General Motors APU in the COMBATT truck is an example of such a system [11]. The designs could be applied to aircraft or ships for long-distance travel, or vehicles such as local utility or transport vehicles that are also used as power sources for activities undertaken at remote locations.

The broad interest in the use of hydrogen in the vehicle market offers considerable potential for Antarctic communities to leverage these technologies in the future. Long-distance transport systems (planes, shipping etc) are being investigated but the potential to produce and storage effective quantities of hydrogen is conceivably a long distance away. It is therefore more effective to focus on small-scale applications which, although representing relatively small amounts of fossil fuels, can perhaps gain the most in environmental or operational benefits through the use of hydrogen technologies.

7.3.2 Challenges facing the use of hydrogen in Antarctic transport systems

A range of challenges can be identified facing the uptake of hydrogen technologies in the transport sector of Antarctic operations:

1. Storage of enough hydrogen in vehicles to meet support travel distances needed
2. Developing supply routes for the fuel – transport from Australia or production on the continent using renewable resources
3. Developing distribution methods for the fuel, and the operational constraints of not sharing a common fuel with other Antarctic nations or operators.
4. Cost of the technology at the present time.
5. Very limited availability of vehicles
6. Developing effective procedures for safety of handling equipment during refueling
7. Power production in the low temperatures of Antarctica
8. Testing and securing adequate service life from equipment

7.4 *Personal or mobile devices*

Antarctica is a harsh and hazardous working environment, particularly for an individual outdoors, but a practical reality of life in Antarctica is that many tasks must be undertaken away from fixed energy supply infrastructure. The resulting dependence on mobile energy supply infrastructure can range in duration from short periods of time for brief tasks within the surrounds of permanent research stations, to months of living in remote field camps with minimal facilities.

Conventional technologies such as gasoline-powered generators, gas heaters or battery packs are used to meet the varied power demands of individuals but are not well suited to the tasks – particularly batteries which hold little charge in cold temperatures.

The role that hydrogen energy technologies can play in the life of an individual in Antarctica could range from enhancing their productivity and ease of work with lightweight and portable power systems to operate their tools and equipment, maximize the safety of their work and travels by powering communications and navigation systems, and improve the quality and comfort of their physical environment such as with heated clothing. The hydrogen power system used with a laptop computer illustrated in Figure 7.13 is one example of how hydrogen technologies could replace conventional batteries in field environments. The hydrogen system would provide longer energy services to the component and be less impacted by the cold temperatures (on losing charge) compared to a battery. If the fuel cell used in the system was regenerative (i.e. reversible), the storage system could also be recharged in the field (as with a battery) for repeated service.

Figure 7.13: a laptop powered using a fuel cell (model A25) operating on hydrogen fuel stored in a block-shaped metal hydride canister. Image from "Smart Fuel Cell" (www.efoy.de).

Hydrogen energy technologies may also be of particular assistance in the event of emergencies, providing a means of heating, light, location fixing and communication. Hydrogen technologies such as fuel cells operating on pure hydrogen or hydrogen-rich materials such as ethanol offer the greatest potential to meet the energy needs of individuals living and working in the Antarctic environment.

Opportunities are emerging for early markets for hydrogen technologies due to the limited performance of existing systems, particularly small-scale devices. The global market for hydrogen technologies is predicting the emergence of personal hydrogen-powered devices (e.g. mobile phones) in the next few years, hence this may be one of the earliest potential applications in Antarctic operations.

7.5 Automated and remote research equipment

A variety of automated electrical devices and systems are used for research and operational tasks in Antarctica, such as automated weather stations, wildlife tracking equipment, and GPS systems. Hydrogen energy technologies can be used to meet the small but long-term power demands of such systems.

Figure 7.14: A radio repeater showing mast with antenna, the solar array and equipment hut at Mt Elder on Macquarie Island (left). Beche Island Automatic Penguin Monitoring Systems (right). AAD photographs.

Maintaining a human presence at such facilities is very unattractive for a wide range of reasons ranging from the expense, inefficiency, environmental impacts, and above all – the lack of demand for a human presence given the levels of technological capabilities that are currently available to operate automated equipment in remote regions. Current energy systems for these facilities are based on the use of batteries and/or renewable energy technologies.

Some applications cannot be served with these technologies, and the expense and unsuitability of establishing more conventional (direct human operation) energy systems prevent their use. As a consequence, these actions do not occur. In other applications, the complexity and expense of deployment and potential environmental footprint of the energy system prevents the initiation of scientific experiments in remote locations.

Rapidly growing development in the use of automated operations for non-Antarctic science applications suggests that there are many emerging opportunities for expanded range of remote equipment in Antarctica. Enhancements in data acquisition, data storage and communication will enable much greater collection of scientific data in the future. Energy supply capability is the limiting factor for operation.

Hydrogen technologies can offer advantages over conventional systems for such applications. They can serve roles as the energy storage component in a renewable energy RAPS with greater energy storage, reducing the impact of the cold Antarctic conditions on energy storage. Hydrogen technologies could also be applied as a delivered fuel and conversion system 'in a box' that does not require deployment of PV panels.

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9. Hydrogen consumption from supplier's specifications is 1.3 L/min per 100 W at 100% load
   Therefore H2 consumption for 1000 W = 13 (L/min)/kW;
   Consumption for 1 kWh = 13 (L/min)/kW x 60 min/h = 780 L/kWh

   Therefore, Magills prediction of 7 kWh/day = 5460 L/day
   With each bottle holding 30600 L, = 5.6 days per bottle.

   Pointing's prediction of 2.5 kWh/day = 1950 L/day
   With each bottle holding 37500 L, = 15.7 days per bottle
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Chapter 8. Simulation of a wind-hydrogen system for Mawson

This chapter investigates the use of hydrogen energy storage technologies at the permanent Australian Antarctic station 'Mawson' through the application of detailed computer simulations of the station's energy system. The experiments are designed to investigate the conditional use of existing hydrogen energy system tools and models to represent functioning Antarctic stations, and explore the implications of using various energy system designs and components. The simulations utilise 'real world' data provided by the Australian Antarctic Division, and conclude that the integration of hydrogen technologies into the existing wind-diesel system is technically feasible and can further reduce the diesel consumption of the station beyond that achieved with only the turbines.

8.1 Introduction

The information and analyses presented in the preceding chapters suggest that it is theoretically viable to utilise hydrogen technologies and renewable energy resources to meet the energy needs of Antarctic communities. It is further suggested that the use of such technologies will provide benefits to the communities due to the reduced need for the importing of fossil fuels (diesel).

However, if hydrogen technologies are to be seriously considered for use by Antarctic communities, an improved understanding is needed of the practical implications and technical realities of their operation in specific and genuine energy use scenarios. This understanding includes knowledge of the practical sizes of hydrogen energy system components, their performance characteristics when working in partnership with local energy resources to meet realistic energy demands, and the true magnitude of possible diesel fuel savings for the communities. Developing such an understanding of the operation of energy systems is routinely achieved through the application of computer modelling tools to generate time-based simulations of the energy flows within the systems [1].

This study applies and evaluates computer modelling tools to investigate the integration of hydrogen technologies into one of the largest and best suited facilities in Antarctica - Mawson Station. The modelling results will complement the analysis of general operations and potential roles of hydrogen technologies, as covered in Chapter 7. The results are directly relevant to the user community as Mawson Station is currently being developed with the intention of integrating hydrogen technologies in the future.

The specific objectives of the study are:

1. To determine the technical viability of operating Mawson Station as an energy-independent facility that utilises local wind resources for primary energy generation and hydrogen energy technologies for energy storage, including identifying suitable operating parameters.
2. To investigate the viability and relative performance of the system configured for *objective 1* but with a number of modifications, including changes in system designs, user loads, component performance and allowing limited dependence (<20%) on fossil fuels for energy generation.

3. To evaluate the suitability and capability of computer simulation and modelling resources as important tools for energy-using communities and system designers to identify viable energy supply options.

This chapter presents only a summary of key information relating to these experiments and related results. More detailed and supplementary information related to the chapter is included in Appendices 2, 3 and 4.

8.2 Summary of the modelling tools, data sources and processes

The modelling activity focused on the detailed analysis of the integration of hydrogen energy technologies into the existing wind-diesel energy system at Mawson Station in Antarctica. Various configurations of hydrogen energy (H_2) storage systems were used to store excess energy produced by the station's wind turbines. The hydrogen systems were then employed to meet the station's electrical, heating and water production loads during periods of insufficient wind power.

The energy system design was based on the replacement or duplication of the existing centralised diesel power system with a hydrogen energy system. This design was chosen over more complex systems, such as those evaluated in Chapter 7 (roles of hydrogen), as it is the simplest application of hydrogen technologies in such a situation. It was viewed as an appropriate starting point for the first use and evaluation of hydrogen technology modelling tools in such energy use scenarios. The station's energy system design was also simplified to effectively simulate the existing combined heat and power (CHP) system, with a number of assumptions made in the modelling process to represent the station's heating load. The reasoning for this decision is detailed in Appendix 2. This resulted in a two-stage analysis process whereby the electrical energy flows in the energy system were calculated using detailed computer simulations, and thermal energy balancing was undertaken with post-simulation analysis.

The core components that were modelled in the project and the inputs and outputs that were included in the analysis are detailed in Figure 8.1.

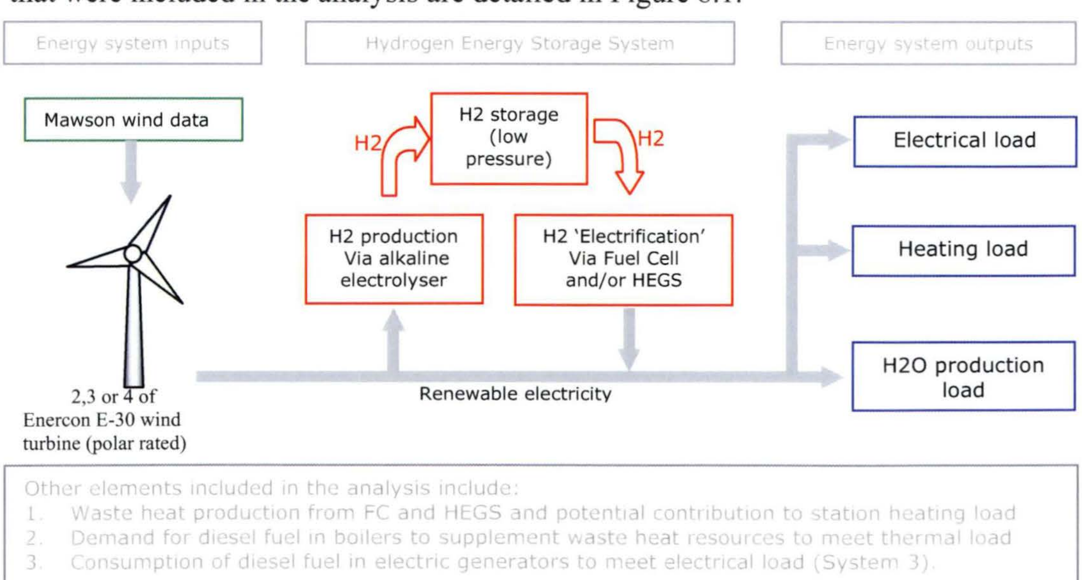


Figure 8.1: core components of the Mawson H_2 system model.

8.2.1 Energy system designs used in simulations

Three configurations of wind-hydrogen energy systems were evaluated, as illustrated in Figure 8.2:
System 1: a wind-H2 system using only a fuel cell (FC) for hydrogen conversion.
System 2: a wind-H2 system that used a single FC and a conventional electric generator configured to operate on hydrogen (HEGS) for hydrogen conversion;
System 3: a wind-H2-diesel system using a fuel cell for stored energy conversion, assisted by a conventional diesel-fuelled electric generator (DEGS).

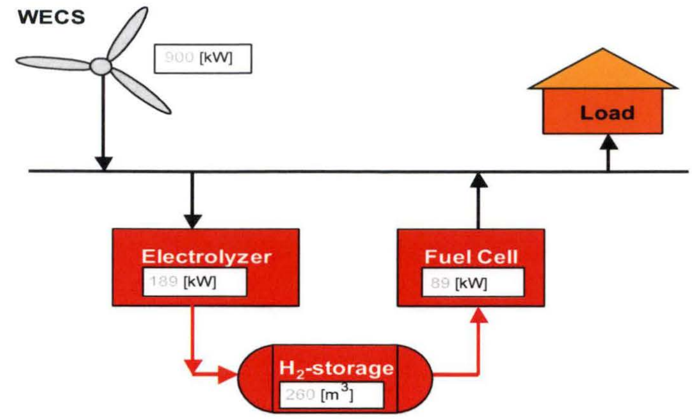
The specific components included in the model were: two, three or four Enercon E-30 wind turbines (polar modified), as currently installed at Mawson Station; an alkaline electrolyser for hydrogen production from water; low pressure (200 bar) hydrogen storage tanks; and a fuel cell (FC) and/or electric generator (HEGS) for electricity and heat generation from hydrogen fuel. A diesel electric generator (DEGS) was also used in system 3, and conventional diesel fuelled boilers were utilised in the post-simulation analysis for thermal energy balancing.

The modelling process sought to identify viable designs for the three systems through manipulation of the key size specifications for the major system components (e.g. the rated power of the fuel cell component). Analysis of the systems included variations to a number of parameters, including:

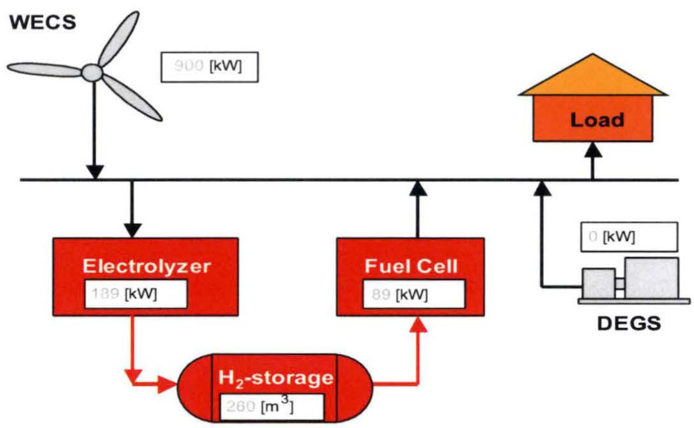
1. Load profile – two load profiles (*practical* and *conservative*) were utilised: the practical profile included only electrical loads in the model and assessed thermal loads after the simulations. The conservative profile integrated the electrical and heating loads of the station into a single data file.
2. Energy independence of the station, or demand for imported fossil fuels
3. Maximum electrical energy loads (180 kW – 220 kW)
4. Energy consumption of the electrolyser component during idling mode (electrolyser idling load, EIL) of 40% EIL and 10% EIL

For the sake of clarity, the following exclusions are also noted for the project:

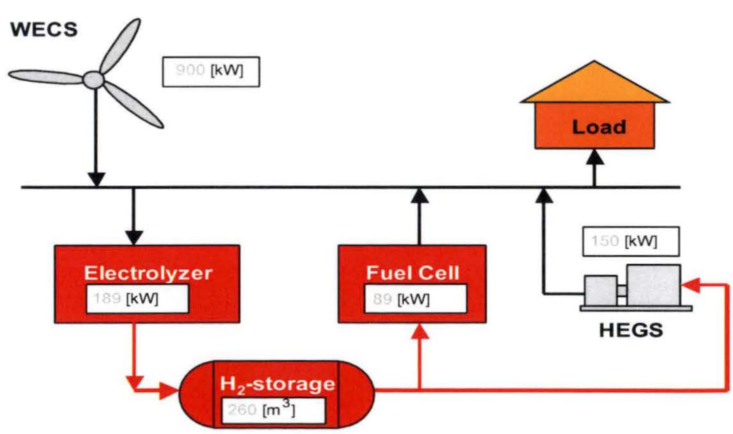
1. This project did not include analysis of other techniques to integrate energy storage technologies into Antarctic stations
2. This project did not include post-simulation assessment methods such as economic or life cycle analysis.
3. This project did not conduct analysis of other Antarctic stations.



System 1: Wind / Electrolyser / Hydrogen Storage (H_2)/ Fuel Cell (FC)



System 2: Wind / Electrolyser / H_2 / Fuel Cell / Diesel Engine Gen Set (DEGS)



System 3: Wind / Electrolyser / H_2 / Fuel Cell / H_2 Engine Gen Set (HEGS)

Figure 8.2: The three energy system designs used in simulations.
(component sizes are examples only).

8.2.2 *Modelling tools used for wind-hydrogen system simulations*

The tools used in this modelling project were based upon the HYDROGEMS 'tool box' – a practical and conceptual library of hydrogen energy technology-specific models developed by Dr Øystein Ulleberg at the Institute for Energy Technology (IFE) in Norway [2]. The HYDROGEMS toolbox is a high resolution and high quality modelling resource and was considered to be the best of its type at the time of evaluation in 2002. This opinion has been confirmed through close collaborations with Ulleberg and externally proven via the growing number of users and successful modelling projects that have emerged in recent years [3].

The HYDROGEMS toolbox is the product of over a decade of investment in development and refinement, quality control, and application by Ulleberg and other researchers. The toolbox is currently being applied in high-level projects such as the International Energy Agency Hydrogen Implementing Agreement – Annex 18 Integrated Systems Task B[4]. At the time of selecting the modelling tools for this research project, the most recent version of the toolbox had also been applied in the evaluation and design of the Utsira Island (Norway) wind-hydrogen demonstration project [5][6]. This project bore strong correlations with the Mawson system and experiences developed through the Utsira Island project were used to improve the model before its application to Mawson.

The HYDROGEMS toolbox utilises two core software packages (TRNSYS and EES programs) that are available from commercial suppliers, and a freely available library of discrete renewable and hydrogen energy component models [7][8].

A number of factors were considered in selecting the use of this pre-existing model over the development of a dedicated model for the Mawson system. The model's history of development, field testing and improvement by a world-recognised expert (Ulleberg) over a ten-year period were the most convincing issues. Analysis of other models and modelling tools also indicated that the pre-existing model itself (in addition to the software used to develop the model) was representative of the state of the art of hydrogen-specific energy system modelling at the time.

A number of potential disadvantages, however, were also identified in relation to the use of the pre-existing model. They included limited control over the system design (component selection and specifications) and 'softer' elements of the simulation process, such as the tailoring of a control system for the unique characteristics of the situation. This issue was deemed to have the greatest impact on the ability to model the combined heat and power (CHP) energy system of Mawson Station.

Most conventional remote area power systems (RAPS) do not use CHP systems. They also do not include sophisticated hydrogen energy systems. Whilst the pre-existing model was able to effectively simulate the integration of novel hydrogen energy technologies into RAPS, it was not designed to consider CHP operation. The model was constrained to represent the thermal energy demands of the user by integrating heating loads and other electrical energy demands into a single load profile. This process was consistent with the operation of many RAPS where thermal energy demands were met with electrical heating or wholly separate heating systems.

In contrast, the Mawson CHP system is highly sophisticated and captures a high proportion of waste heat energy from combustion energy sources (diesel generators) and 'wasted' wind energy. The heating load of the station also represents approximately half of the station's total annual energy demand, a situation that is not experienced by energy users in more conventional climates. This provides opportunities for significant energy savings at the station. The techniques used could be relevant for energy users in similar climates.

The development, however, of an effective model of the CHP energy system for a conventional diesel and/or wind-diesel energy system was determined to be a significant challenge, without considering the integration of hydrogen energy storage components. The complications associated with integrating hydrogen energy technologies into a wind-diesel CHP model for Mawson were subsequently deemed to be beyond the scope of this research. Although there would be considerable value in developing models for CHP wind-H2 systems, it was decided that this research program would focus on conducting a first-level analysis of the use of hydrogen technologies at Mawson. The outcomes from the analysis would assist in evaluating the merit of developing specific energy system models for Antarctic stations. The use of an expert-developed and proven model from a system with many comparable characteristics to the Mawson study was also seen to offer time and performance advantages that far outweighed the potential disadvantages associated with using the model.

It must be noted that use of Ulleberg's model still required the author to develop a comprehensive understanding of the modelling process and the history of development of the specific model. This knowledge was used to modify the model to execute the simulations for Mawson Station and to understand the capabilities and vulnerabilities of the simulation tool. Understanding the operation of the model was also essential for interpreting the results from the simulations.

Following this route of utilising existing (and state-of-the-art) modelling resources also enabled the evaluation of the suitability of these resources for use by energy-using communities such as Antarctic programs rather than by energy system developers.

The modelling component of the research was undertaken over a period of twelve months, including two visits to the IFE in Norway for training in the use and modification of the simulation tools (HYDROGEMS toolbox) and guidance with data file preparation and result interpretation. Expertise developed with the tools was subsequently applied in co-hosting with Ulleberg a workshop on hydrogen energy system modelling in September 2004, which was attended by 15 representatives from academia, industry and government [9]. These modelling skills were also utilised in extending the modelling and analysis undertaken for this research as a component of the Mawson Hydrogen Demonstration Project.

As the pre-existing model was only capable of accepting a single load profile, suitable approaches needed to be devised to appropriately represent the CHP capability of the station.

8.2.3 Data sets used to simulate Mawson Station

Modelling data sets were developed after extensive processing of available and appropriate data provided by the AAD, including electrical and heating loads, wind speeds and a power curve for the modified wind turbines installed at Mawson.

The wind speed data set was primarily based on data from 2003, but incorporated lower resolution data from a 44-year period (1955-1998). The electrical load data was generated from the profile of energy usage in 1999, with an hourly normalised load profile (values of 0 to 1) multiplied by a revised maximum electrical load of 200 kW (resolved through discussions with AAD personnel). The thermal load data was based on data from 2002.

Further details of the evaluation of the wind speed and load data and subsequent generation of the data files are presented in Appendices 2 and 3. Images of the data sets are presented in Figures 8.3 – 8.7 following.

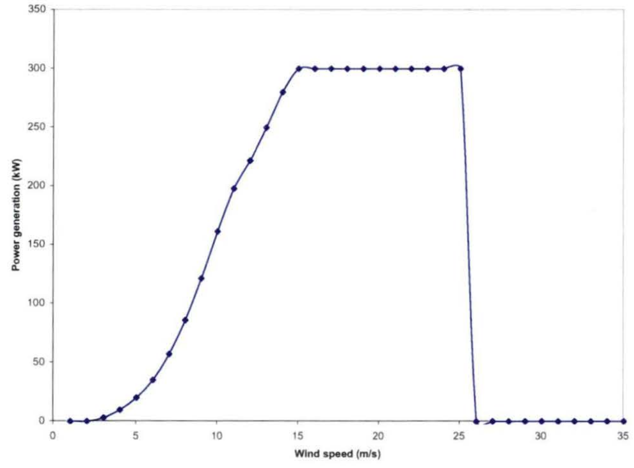


Figure 8.3: Power curve for Enercon E-30 (polar rated) wind turbines used at Mawson Station (34 m hub height), as supplied by AAD.

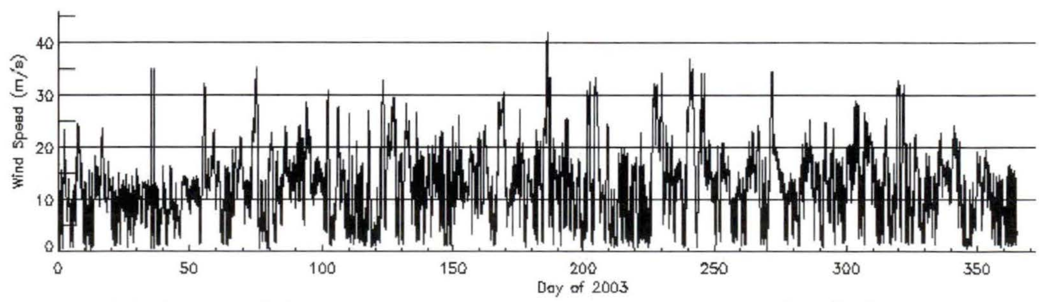


Figure 8.4: Reference wind speed data set for Mawson Station compiled primarily from data from 2003 (30m measurement height).

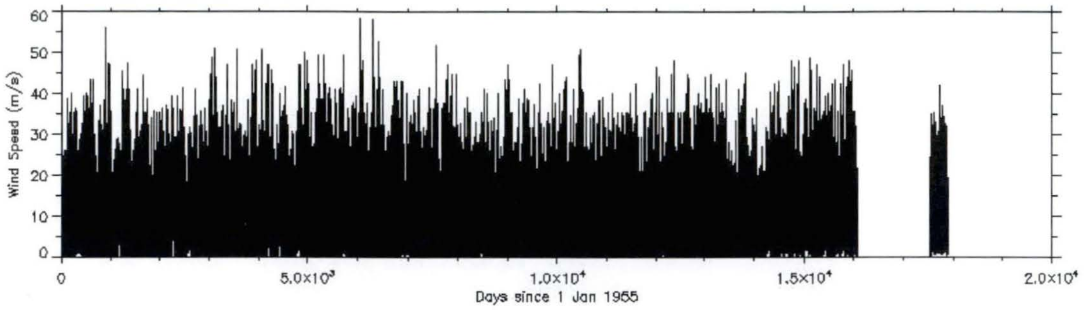


Figure 8.5: Processed 'historic' wind speed data set for Mawson Station, (1956–1998 + 2003, 30m measurement height).

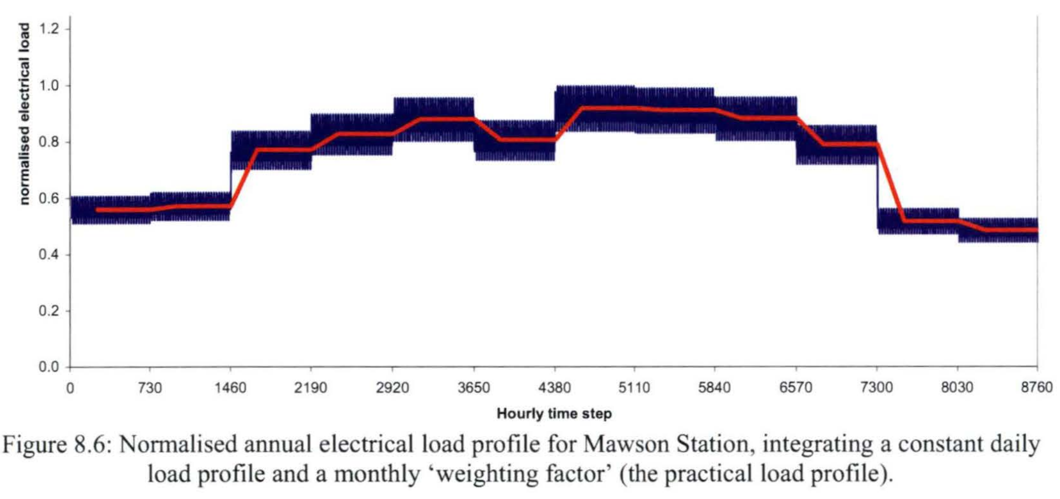


Figure 8.6: Normalised annual electrical load profile for Mawson Station, integrating a constant daily load profile and a monthly 'weighting factor' (the practical load profile).

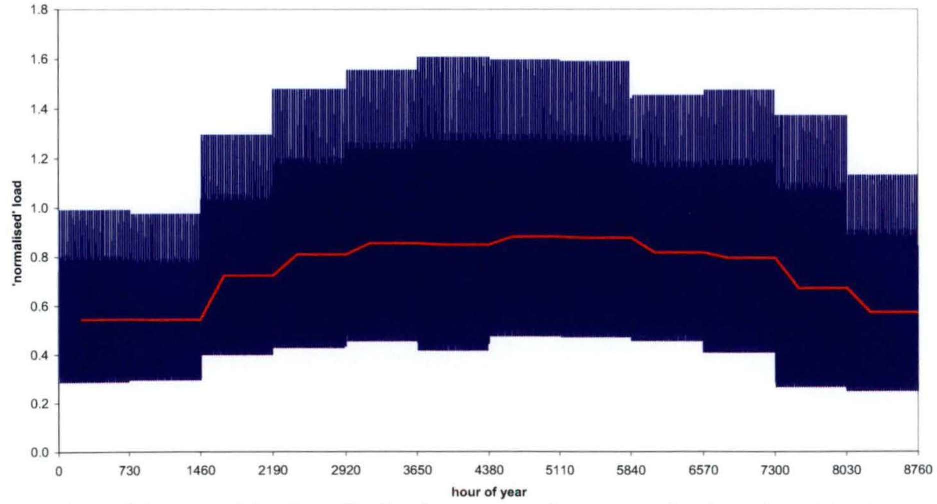


Figure 8.7: Annual load profile for the conservative approach - forced total load.

8.2.4 Summary of the modelling process

The HYDROGEMS simulation toolbox was used to execute time-series simulations of the three energy system designs. Each simulation operated with one-hour data intervals over a period of one year, analysing the performance of the system with respect to different component sizes relative to the wind energy resources and station loads.

As noted previously, two load profiles (practical and conservative) were used in the simulations. Both profiles were developed from the user's load data and converted in normalised load values. These profiles were linked by the modelling software to the maximum load specified for the simulation. This enabled the loads to be varied without changing the individual load profile.

The majority of experiments or simulation runs were conducted using the practical load profile. A two-stage analysis technique was used to identify and assess the energy system configuration. The first stage identified the size of hydrogen conversion components (e.g. fuel cell) needed to fully meet the electrical energy demands of the station using the wind-hydrogen technologies, without consideration of the thermal demands of the station. The second stage determined the viability of using the excess wind energy and waste heat in the system to meet the station's thermal load, and subsequently the amount of fuel required to meet any thermal load deficit using diesel-fired boilers.

Experiments with the conservative load profile used a single analysis step to identify the size of the energy system components needed to meet the thermal and electrical energy demands of the station.

The key processes involved in the simulations and analyses included:

1. Specifying sizes for individual components in the hydrogen energy storage and conversion system, with an excessively large hydrogen storage capacity.
2. Optimising the component sizes with the objective of minimising component sizes whilst requiring a specified amount of imported energy (0 kWh per annum for most simulations).
3. Optimising the hydrogen storage volume following the principle in (2).
4. Repeating (1) – (3) above but beginning with the optimised storage volume from (3) to reach a fully optimised system design. This process reduces the influence of interconnected energy flows between the components on the optimisation process. For example, a smaller hydrogen storage system would reduce the true operating time of an electrolyser as it would stop once the storage tank was full. That may enable a smaller electrolyser to be used. A smaller electrolyser would have a smaller parasitic load on the fuel cell, which would consume less fuel from the storage system to meet the idling load of the electrolyser, enabling further reductions in storage system size.
5. Analysis of the annual energy system budget (import/export of energy).
6. Analysis of individual component utilisation. For example, percentage of operating time that the fuel cell works in the power band of 90-100% of its rated power, or percentage of time that the FC is idle.
7. Post-simulation analysis of the thermal energy performance of the energy system through review of excess wind energy potential and waste heat generation from fuel cell (and HEGS) component (for practical load only).

Solutions for each system configuration were deemed successful if the design demonstrated (through the simulations) an ability to operate for a calendar year without failure or unacceptable demand for imported energy resources, made maximum effective use of components with minimum-sized components, and had comparable levels of stored hydrogen at the start and end of year.

For experiments using the practical load profile, the process was designed to enable conservative but accurate system simulation and analysis using proven tools and procedures. The technique focused on the time-critical electrical energy demands of the station that must be met using the wind and stored hydrogen energy reserves. The thermal energy loads of the station were also addressed, but it was assumed that the 12-hour storage capacity of the heating system could adapt to short-term deficits in thermal energy.

For experiments with the conservative profile, the process was designed to eliminate the need for the two-stage assessment process. However, it was also expected to result in some level of over-sizing of the hydrogen energy system as the combined thermal and electrical loads would potentially rely completely on the hydrogen energy system at some period during the year. The main flaws of the approach were seen to be that heating loads that could potentially be delayed by up to 12 hours were given the same degree of immediate response as electrical loads and no calculation of waste heat potential was included.

The figures for component performance were either supplied by the AAD or identified in collaboration with hydrogen energy system modelling experts at IFE.

Executing the models and evaluating the results required a combination of manual and automated tasks, including the entry of key simulation parameters into a graphical interface, execution of the simulation, initial evaluation of results, second order evaluation of results, and identification of optimised system designs for each combination of simulation conditions. Between 1000 and 1500 simulations were undertaken during the study. Final analysis of the system designs was completed with Excel spread sheet software. Further details of the simulation process are presented in Appendix 2. A worksheet developed by the author for general modelling activities using the HydroGEMS toolbox is presented in Appendix 4.

8.3 *Summary of Experimental Results*

The energy system modelling experiments focused on 5 key aspects of the design and operation of a wind-hydrogen(-diesel) system for Mawson Station, including:

1. Load profile used in the simulations,
2. Specified dependence on imported energy (operating goal)
3. System design (System 1, 2 or 3) and included components
4. Power consumption of the electrolyser during idle operation
5. Electrical load at the station (200 kW +/- 10%)

The experiments undertaken are presented in Table 8.1 below. As illustrated in the table, the majority of experiments applied the practical load profile.

Load profile	*Energy import*	*System Design*	*Electrolyser Load at Idle*	*Electrical load*
Practical load	100 % independent operation	System 3	40 % EIL	180 kW
				200 kW
				220 kW
			10 % EIL	180 kW
				200 kW
				220 kW
		System 1	40 % EIL	200 kW
	~80% independent operation	System 2	40 % EIL	200 kW
Conservative load	100 % independent operation	System 3	40 % EIL	200 kW

Table 8.1: Experimental program for the computer modelling of wind-hydrogen energy systems at Mawson Station, Antarctica.

Common features of the system designs, unless specified otherwise, included:

1. 3 wind turbines were installed (except when 2 or 4 turbines are assessed),
2. 200 kW peak electrical loads and a total annual heating load of 2020 MWh,
3. Use of the practical load profile for the computer simulations,
4. The electrolyser component switched into idle mode when not producing hydrogen, with an idle demand load (EIL) of 40% of rated power,
5. The FC components switched into idling mode when not operating to meet user demand for electricity, with an idling power electricity output and corresponding hydrogen consumption of 5% of rated power,
6. The AC-DC converters on the FC and electrolyser had conversion efficiencies of approximately 87%,
7. The HEGS component switched off when not needed for electricity production, and was only used when the electricity provided by the FC and wind was insufficient to meet the electrical load of the station.
8. Waste heat available from the FC and HEGS was captured at 30% efficiency, based upon the performance of the existing diesel-based CHP system.

9. The volume of hydrogen stored in the system's tanks at the start and end of the year needed to be approximately identical. The initial volume of hydrogen storage was determined as part of the optimisation process.
10. The volume of stored hydrogen could not be depleted below 10% of the total storage capacity. This constraint relates to the practical viability of extracting 100% of stored gas reserves and a safety factor to maintain a minimum reserve of hydrogen fuel on station.

Further details of the analysis methods and results are available in Appendix 2.

8.3.1 Systems 1 and 3, seeking 100% energy independent operation, with 200 kW practical load, conventional electrolyser (40% EIL), and 3 wind turbines

These experiments sought to determine if the three wind turbines installed at the station, when partnered with optimised hydrogen energy storage systems, could provide sufficient energy to meet the station's thermal and electrical energy demands without the need for imported energy sources (such as diesel). The experiments were conducted using Systems 1 (FC only) and 3 (FC + HEGS).

The two-stage process of assessing the system performance was applied to each system. Details of the system configurations that met the station's electrical energy loads without dependence on imported energy resources, with optimised component sizes, are presented in Table 8.2. The first stage of the assessment also included high resolution analysis of the simulation results to assess the performance of individual components and the viability of the results. This post-simulation analysis indicated that the sizes specified by the models for the fuel cell component could be reduced by approximately 33% in each system. The corrected results are subsequently presented.

	System 1 FC only (corrected)	System 3 FC + HEGS (corrected)
Peak load (kW)	200	200
Elyzer rated power (kW)	320	356
FC rated power (kW)	399	100
HEGS rated power (kW)	0	275
Total generation capacity (kW)	399	375
H2 storage vol (m^3)	365	375

Table 8.2: Component sizes for Systems 1 & 3 (200 kW practical load).

The second stage of the assessment process determined if additional energy reserves were available within the energy systems to also meet the station's annual heating load. This was assessed on a monthly and annual basis. Potential sources of energy included excess wind energy and waste heat captured from the fuel cell and/or HEGS components. The variations in fuel cell size specified by the model were also included in calculations for excess and waste heat availability. Results for systems 1 and 3 are presented in Table 8.3.

	System 1 FC only	System 3 FC+HEGS
Annual heat load in 2002 (MWh/year)	2020	2020
Annual electrical load from simulation (MWh/year)	1307	1307
Total user energy demand (MWh/year)	3327	3327
Excess electrical energy in system (from simulation) (MWh/year)	1580	1304
Extra excess electrical energy (secondary analysis) (MWh/year)	195	64.5
Total excess electrical energy (MWh/yr)	1775	1368.5
Available waste heat from model (MWh/year)	255	211
Total available heat energy (MWh/year)	2030	1579.5
Surplus heat energy		
rel. to 2002 load (MWh/year)	10	-440.5
rel. to 2002 load (% of total heat energy)	0.5	-21.8
Heat load reduction required (% of 2002 load)	-0.5	21.8
SAB consumption for thermal balance (L/year)	0	59932
SAB consumption for electrical load (L/year)	0	0

Table 8.3: Overall performance of Systems 1 & 3 (200 kW practical load).

8.3.2 System 2, seeking ~80% energy independent operation, with 200 kW practical load, conventional electrolyser (40% EIL), and 3 turbines

The experiments with System 2 sought to identify a wind-hydrogen system configuration that would enable significant (~80%) but not total independence from imported energy resources to meet the energy demands of Mawson Station.

The experiments applied similar system components and parameters to those used with System 1, with the use of only a fuel cell for hydrogen conversion to electricity (and waste heat). The design also allowed a proportion of the station's electrical energy demands to be met using imported diesel fuel converted through a conventional diesel electric generator (DEGS), emulating the role of the HEGS in System 3. The performance of the fuel cell, electrolyser and other components were identical to those in System 1. The DEGS component only generated power when the electricity demand in the system exceeded the supply provided by the wind and/or FC, otherwise operating in an idling mode at 5% of rated power.

The two-stage assessment process was applied. The component sizes of an optimised system suitable for meeting a 200 kW *practical* (electric-only) load using a hybrid wind-hydrogen-diesel system with ~20% dependence on imported diesel fuel are presented in Table 8.4. The results from the thermal energy analysis are presented in Table 8.5.

	System 2 FC + DEGS (corrected)
Peak load (kW)	200
Elyzer rated power (kW)	25
FC rated power (kW)	85
DEGS rated power (kW)	140
Total generation capacity (kW)	215
H2 storage vol (m^3)	65
Diesel fuel consumption (L/year)	120441

Table 8.4: Component sizes for System 2 (200 kW practical load).

	System 2 FC + DEGS
	3 turbines
Annual heat load in 2002 (MWh/year)	2020
Annual electrical load from simulation (MWh/year)	1307
Total user energy demand (MWh/year)	3327
Excess electrical energy in system (from simulation) (MWh/year)	3545
Extra excess electrical energy (secondary analysis) (MWh/year)	171.6
Total excess electrical energy (MWh/yr)	3716.6
Available waste heat from model (MWh/year)	104
Total available heat energy (MWh/year)	3820.6
Surplus heat energy	
rel. to 2002 load (MWh/year)	1801
rel. to 2002 load (% of total heat energy)	89.1
Heat load reduction required (% of 2002 load)	-89.1
SAB consumption for thermal balance (L/year)	0
SAB consumption for electrical load (L/year)	120441

Table 8.5: Overall performance of System 2 (200 kW practical load).

8.3.3 *Integrated summary of model results for Systems 1, 2 and 3*

	System Results			Comparisons		
	System 1	**System 2**	**System 3**	S1 - S3 (% Δ)	S2 - S3 (% Δ)	S2 - S1 (% Δ)
Component specifications						
Peak load (kW)	**200**	**200**	**200**	0	0	0
Elyzer rated power (kW)	320	25	356	-10.1	-93.0	-92.2
FC rated power (kW)	399	85	100	299.0	-15.0	-78.7
HEGS/DEGS rated power (kW)	0	140	275	n/a	-49.1	n/a
Total gen capacity (kW)	399	225	375	6.4	-40.0	-43.6
H2 storage vol (m^3)	365	65	375	-2.7	-82.7	-82.2
Summary Energy Balance						
Total input/output (MWh/yr)	5472	5058	5411	1.1	-6.5	-7.6
Energy to user load (MWh/yr)	1307	1307	1307	0.0	0.0	0.0
Energy to user load %	24	26	24	0.0	2.0	-2.0
Energy excess (MWh/yr)	1590	3549	1305	21.8	172.0	123.2
Energy excess %	29	70	24	5.0	46.0	-41.0
Component evaluation						
Electrolyser						
% time at idle / off	32	33	35	-3.0	-2.0	-1.0
% time at 90-100% load	60	66	57	3.0	9.0	-6.0
Total operating hours	8760	8760	8760	0	0	0
Elyzer output energy (MWh/yr)	2574	202	2801	-8.1	-92.8	-92.2
Consumption of system load (%)	47	4	52	-5.0	-48.0	43.0
Fuel Cell						
% time at idle / off	71	91	89	-18.0	2.0	-20.0
% time at 90-100% load	0	0	0	0.0	0.0	0.0
Total operating hours	8760	8760	8760	0.0	0.0	0.0
FC input energy (MWh/yr)	751	65	101	643.6	-35.6	-91.3
Contribution to energy input (%)	14	1	2	12.0	-1.0	13.0
HEGS/DEGS						
% time at idle / off	n/a	77	69	n/a	8.0	n/a
% time at 90-100% load	n/a	11	17	n/a	-6.0	n/a
Total operating hours	n/a	8760	2803	n/a	212.5	n/a
HEGS input energy (MWh/yr)	n/a	273	589	n/a	-53.7	n/a
Contribution to energy input (%)	n/a	5	11	n/a	-6.0	n/a
Combined HEGS/DEGS + FC						
Input energy (MWh/yr)	751	338	690	8.8	-51.0	-55.0
Contribution to energy input (%)	14	6	13	1	-7.0	-8
WECS						
Total operating hours		8164				
WECS Input energy (MWh/yr)		4721				
Contribution to energy input (%)	86	93	87	-1	6.0	-1
Mass Balance						
Fuel cell (Nm^3/yr)	525839	42561	65746	699.8	-35.3	-91.9
FC value (kWh/Nm3)	1.43	1.53	1.54	-7.0	-0.6	6.9
FC&HEGS value (kWh/Nm3)	n/a	n/a	1.17	n/a	n/a	n/a
Diesel for electrical load (L/yr)	0	120441	0			
Diesel for heating load (L/yr)	0	0	59932			

Table 8.6: Comparative summary of system size and performance results for Systems 1, 2 and 3 (200 kW practical load).

8.3.4 *Performance of System 3 with 10% increase or decrease in user load*

The electrical energy demand data used for Mawson Station was based on genuine usage statistics from the station. Past experience has indicated, however, that electrical energy demands at the station can change over time. Key factors include the station population, the activities undertaken at the station and the equipment subsequently used by the personnel on-site. The upgrading of existing equipment in the energy infrastructure or deliberate efforts to reduce energy use can also have large impacts on the station's energy demand and load profile. It was therefore seen as prudent to evaluate the potential impact on the hydrogen energy system configuration if the station's electrical energy load were to increase or decrease by 10% relative to the current reference load of 200 kW. The analysis was conducted using the System 3 design and operating parameters as specified in section 8.3.1, including the use of an electrolyser with an idling load power demand of 40% of rated power. The hydrogen energy system sizes and comparisons to the reference load are presented in Table 8.7. The fuel cell sizes have been corrected with a 30% reduction in capacity.

	Model results			Rel. to 200 kW load	
				180 kW (% Δ)	220 kW (% Δ)
Peak load (kW)	**200**	**180**	**220**	-10	10
Elyzer rated power (kW)	356	295	455	-17.1	28
FC rated power (kW)	100	87.5	143.5	-12.5	44
HEGS rated power (kW)	275	250	300	-9.1	9
Total gen capacity (kW)	375	337.5	443.5	-10.0	18
H2 storage vol (m^3)	375	310	490	-17.3	31

Table 8.7: Component sizes for System 3 (180-220 kW loads).

Details of the systems' capability to meet the station's thermal energy demands and dependence on imported fossil fuels are presented in Table 8.8. In comparison, the reference system (200 kW load) required ~60,000 L of diesel to balance the thermal load.

	System 3, 40% EIL	
	180 kW	220 kW
Annual heat load in 2002 (MWh/year)	2020	2020
Annual electrical load from simulation (MWh/year)	1176	1438
Total user energy demand (MWh/year)	3196	3458
Excess electrical energy in system (from simulation) (MWh/year)	1754	693
Extra excess electrical energy (secondary analysis) (MWh/year)	37.6	61.7
Total excess electrical energy (MWh/yr)	1792	755
Available waste heat from model (MWh/year)	173.2	273.6
Total available heat energy (MWh/year)	1964.7	1028.3
Surplus heat energy		
rel. to 2002 load (MWh/year)	-55.3	-991.7
rel. to 2002 load (% of total heat energy)	-2.7	-49.1
Heat load reduction required (% of 2002 load)	2.7	49.1
SAB consumption for thermal balance (L/year)	5339	89346
SAB consumption for electrical load (L/year)	0	0

Table 8.8: Overall performance of System 3 (180 kW and 220 kW loads).

8.3.5 *Performance of System 3 when using electrolyser with more efficient power usage in idling mode (10% EIL), assessed over differing loads*

The electrolyser component specified in the original System 3 evaluation consumed energy during idle operations (not actively producing hydrogen) that was equivalent to 40% of its rated power. This characteristic was based on the current performance of commercial components available in the market [10][11]. Generic analysis of hydrogen energy system operations suggests that a reduction in the energy consumed by the electrolyser during non-productive periods would result in significant improvements to the energy system sizing and performance. Such a reduction could be achieved in a number of ways, including reducing the idle power consumption or enabling the component to turn off rather than operate continuously.

The potential impacts of reducing the idle power consumption were assessed within the models by specifying an idle power load of 10% of rated power, with the other system parameters remaining consistent with the original System 3 design. The system performance was also assessed with 10% increases and decreases in electrical load. The hydrogen energy system component sizes are presented in Table 8.9, with comparison to the results for System 3 operating with the conventional electrolyser (40% EIL) in Table 8.10. The total system performance and demand for imported energy for System 3 with the 10% and 40% EIL components is presented over in Table 8.11. As with the original System 3 design (40% EIL), the system aims to achieve 100% energy independence, and was assessed using the two-stage method.

	System 3, 10% EIL			Rel. to 200 kW load (% Δ)	
				180 kW	220 kW
Peak load (kW)	200	180	220	-10.0	10.0
Elyzer rated power (kW)	189	158	212	-16.4	12.2
FC rated power (kW)	89	80	100	-10.1	12.4
HEGS rated power (kW)	150	140	164	-6.7	9.3
Total gen capacity (kW)	239	220	264	-7.9	10.5
H2 storage vol (m^3)	259	220	295	-15.1	13.9

Table 8.9: Parameters for System 3 over various loads when using electrolyser with idle power demand of 10% of rated power (EIL).

	40% EIL electrolyser			Rel. to 10% EIL results (% Δ)		
Peak load (kW)	200	180	220	200	180	220
Elyzer rated power (kW)	356	295	455	-46.9	-46.4	-53.4
FC rated power (kW)	100	87.5	143.5	-11.0	-8.6	-30.3
HEGS rated power (kW)	275	250	300	-45.5	-44.0	-45.3
Total gen capacity (kW)	375	337.5	505	-36.3	-34.8	-47.7
H2 storage vol (m^3)	375	310	490	-30.9	-29.0	-39.8

Table 8.10: Comparison of results for System 3 over various loads when using electrolysers with idle power demand (electrolyser idle load, EIL) of 10% and 40% of rated power.

	System 3 FC+HEGS	
	40% EIL	10% EIL
Annual heat load in 2002 (MWh/year)	2020	2020
Annual electrical load from simulation (MWh/year)	1307	1307
Total user energy demand (MWh/year)	3327	3327
Excess electrical energy in system (from simulation) (MWh/year)	1304	2366
Extra excess electrical energy (secondary analysis) (MWh/year)	65	0
Total excess electrical energy (MWh/yr)	1369	2366
Available waste heat from model (MWh/year)	211	96
Total available heat energy (MWh/year)	1580	2462
Surplus heat energy		
rel. to 2002 load (MWh/year)	-441	442
rel. to 2002 load (% of total heat energy)	-21.8	21.9
Heat load reduction required (% of 2002 load)	21.8	-21.9
SAB consumption for thermal balance (L/year)	59932	0
SAB consumption for electrical load (L/year)	0	0

Table 8.11: Overall system performance and demand for imported energy for System 3 with 40% and 10% EIL electrolysers, 200 kW practical load.

8.3.6 System 3, seeking 100% energy independent operation, with 400 kW conservative load, conventional electrolyser (40% EIL), and 3 wind turbines

Modelling with the conservative load profile began with System 3, using a comparable load (400 kW combined heat and electrical) and electrolyser configuration (40% EIL) to that assessed using the practical load profile. The component sizes indicated by the model are detailed in Table 8.12.

	Practical load	*Conservative* load	Compare *Con/Prac*
Peak load (kW)	**200**	**400**	2.00
Elyzer rated power (kW)	356	635	1.78
FC rated power (kW)	100	350	3.50
HEGS rated power (kW)	275	360	1.31
Total gen capacity (kW)	375	710	1.89
H2 storage vol (m^3)	375	600	1.60
Excess energy from model (MWh/year)	1305	14	0.01

Table 8.12: Comparing component sizes for practical and conservative load profiles for system 3, 200 kW, 40% EIL.

As indicated in Table 8.12, the doubling of the maximum user load resulted in a comparable doubling in size for most of the system components, ranging from 160% relative size for the hydrogen storage volume to 190% relative size for the total generation capacity. This included a significant increase in the fuel cell rated power of 350%, balanced by a smaller 130% increase in HEGS capacity.

14 MWh/year of excess energy was available from the system after meeting the station's thermal and electrical loads. The systems consequently had no demand for imported fossil fuels.

8.4 *Discussion of Experimental Results*

8.4.1 *Systems 1 and 3 and achieving 100% energy independent operation*

The experiments with Systems 1 and 3 each sought to identify a wind-hydrogen system that would enable Mawson Station to operate without reliance on imported fossil fuels to meet the station's thermal and electrical energy demands.

The inclusion of the System 1 design enabled the consideration of designs that would be feasible in the long-term and only use fuel cell components, whilst System 3 enabled analysis of more viable near-term designs that used a mixture of conventional and novel hydrogen conversion technologies (FC + HEGS).

The practical load profile and subsequent two-stage analysis technique was used for each system, enabling independent comparison of their capabilities to firstly meet the electrical demands and secondly the thermal loads specified for the system.

The two systems were operated with similar parameters, using slightly different technology configurations in pursuit of the same goal. As summarised in Table 8.13 below, both systems were successful in achieving the system goal of 100% energy independent operation with respect to the electrical load. However, only System 1 achieved overall success with zero dependence on imported fossil fuels. In contrast, System 3 required approximately 60,000 L diesel per year to supplement excess wind energy and captured waste heat to meet the annual heating demands of the station.

	System 1	System 3	System 2
	40% EIL		
Electrical energy independence (%)	100	100	80
Achieved system independence goals	Yes	No	Yes
FC contribution to H2 electricity output (%)	100.0	14.6	100 0
HEGS contribution to H2 electricity output (%)	-	85.4	-
FC rated power (kW)	399	100	85
HEGS/DEGS rated power (kW)	0	275	140
FC conversion efficiency (kWh/Nm3)	1.43	1.54	1 53
HEGS conversion efficiency (kWh/Nm3)	-	1.14	-
FC&HEGS efficiency (kWh/Nm3)	-	1.20	-

Table 8.13: Summary of overall performance for Systems 1 & 3 in achieving goal of 100% energy independence.

The failure of System 3 to achieve 100% energy independence can be directly traced to the use of a HEGS component for conversion of hydrogen to electricity. Combustion engine generators operating on hydrogen (or other fuels) are known to be less efficient than fuel cells, which employ direct chemical conversion methods to generate electricity and heat from hydrogen. This contrast in efficiency is borne out by the results for Systems 1 and 3: the FCs used in both systems were more efficient at producing electricity than the HEGS in System 3. The FC in System 1 was four times the size of that used in System 3 and subsequently had slightly poorer efficiency of conversion. However, it outperformed the smaller HEGS of System 3 even though the FC operated continuously throughout the year and the HEGS component was switched off for ~70% of the year. The fuel cell conversion efficiency figures for System 2 included for comparison in Table 8.13 further demonstrate the higher efficiency of fuel cell components relative to HEGS components. The consequence of this poor efficiency was that System 3 consumed more hydrogen to produce the same amount of energy than did System 1 operating only with a fuel cell.

The relatively poor efficiency of hydrogen conversion for the combined components in System 3 (1.2 kWh/Nm3) resulted in demand for a larger electrolyser (~10%) for hydrogen generation and a larger hydrogen storage capacity (~3%). The larger electrolyser subsequently consumed more power (~8%) than the smaller component in System 1.

The less efficient use of hydrogen fuel in System 3 and the related demand for more hydrogen production when using the same wind resource and turbines reduced the availability of 'excess' energy in the system, as compared to System 1 (by approximately 22% of the total heat load, refer to Table 8.3). As this excess energy was used to meet the thermal energy demands of the station, the reduction in available energy critically impacted the overall performance of System 3 in meeting the station's total energy needs. The energy balance in System 1, utilising the efficiency of the fuel cell component, provided barely sufficient excess wind and waste heat energy to meet the thermal energy demands of the station. System 3, by comparison, required approximately 22% reduction in thermal load to eliminate the demand for the equivalent of ~60,000 L of diesel fuel. The energy content of this fuel is coincidentally equivalent to the energy lost from System 3 due to the poor conversion efficiency of the HEGS and the larger electrolyser.

System 3 does appear to offer an advantage of enabling a smaller total generation capacity compared to System 1. The reduced generation capacity could be seen as a positive benefit to using HEGS components. However, the small difference can be attributed to the conversion from DC-AC power for the fuel cell and the larger relative impact this has on the larger FC in system 1.

Therefore, from a technical perspective, the selection of the HEGS component critically restricts the system's ability to meet the energy needs of the station. Additional primary energy resources (sourced either from delivered fuel or more wind turbines) would be needed to balance the station's annual energy budget.

Technical considerations, however, are not the only important factors influencing the selection of energy system components. Issues such as the cost of components, the availability of products, trained operators and service infrastructure, and the method of integrating novel technologies into existing operations must also be considered.

Fuel cells, for example, are significantly more expensive than converted combustion engines for conversion of hydrogen. Although HEGS are less efficient, the total cost of an H2 system (electrolyser, storage, conversion) may be reduced through the inclusion of less capital-intensive HEGS components. Also, fuel cells are novel technologies with very few suppliers, trained operators or service facilities. This contrasts markedly with the highly established infrastructure networks associated with combustion engines. The operation and servicing of HEGS requires additional training for existing personnel rather than the development of new skill sets for novel fuel cell technologies. A further advantage of HEGS components compared to fuel cells is the opportunity to retro-fit existing infrastructure to operate on hydrogen or hydrogen-diesel fuel blends. This enables full utilisation of the investment in existing infrastructure and the phasing in of hydrogen technologies as appropriate for the users.

8.4.2 Performance of System 2 in achieving ~80% energy independent operation

This component of the modelling experimental program initially sought to identify an energy system configuration that would enable a high level (80%+) of renewable energy penetration into Mawson Station's energy system via the use of hydrogen energy storage. The simulations used the System 2 design of wind-hydrogen-diesel energy system. This utilized a fuel cell (FC) for electricity generation from hydrogen generated on-site via electrolysis of water and excess wind energy, and a diesel electric generator (DEGS) for electricity generation from stored diesel fuel. The DEGS and FC components also enabled capture of exhaust (waste) heat for use in meeting the station's thermal energy demands with a conversion efficiency of 30%. The design assumed the use of 3 wind turbines at the station.

A summary of the energy system performance is presented in Table 8.14.

	MWh/yr
Energy to user electrical load	1307
Energy to user thermal load	2020
Total user energy demand	3327
DEGS electrical energy generation	273
DEGS thermal energy generation	82
Energy contribution from DEGS (electricity + heat)	355
Contribution of DEGS to user's electrical load (%)	20.9%
Contribution of DEGS to total user load (%)	10.7%
Contribution of DEGS to total user load (%) (excluding waste heat contribution)	8.2%

Table 8.14: Summary of overall performance for Systems 2 in achieving goal of ~80% energy independence.

The sizes of the wind-hydrogen energy system components were optimised via the simulation process to achieve approximately 20% dependence on the DEGS component to meet the electrical energy demand of the station. This required the import of approximately 120,000 L of diesel fuel per year.

Post-simulation analysis of the results indicated that the excess energy available within the system (primarily from the 3 turbines) and the waste heat available for capture were more than adequate to meet the station's thermal energy demands. No additional fossil fuels were required, therefore, to meet the station's thermal energy demands, reducing the total system dependence on fossil fuels to 10.9%. The results were based on the assumption that thermal energy could be adequately stored between opportunities for capture (from waste heat and/or excess wind) and periods of user demand.

If the waste heat of the DEGS was not captured to assist in meeting the station's thermal energy demands, the station's dependence on fossil fuels would be reduced further to 8.2% as the excess wind energy could be used to meet the resulting deficit in thermal energy. Pursuing this option, however, would not be logical as the station design is already configured to capture waste heat from the components and the additional excess electrical energy in the system that would be used to meet the heating demand would be more valued if applied to other tasks. Potential applications include the further production of water supplies from ice melting for hydrogen production or domestic use, or the generation of additional hydrogen supplies for use in supporting other energy users (e.g. vehicles or field camps supported by the station).

The configuration specified for System 2 enabled considerable reductions in the size of the hydrogen storage system when compared to those specified for 100% energy independent operation of the station using systems 1 and 3. The production of large amounts of excess or unused energy by System 2, however, suggests that further design improvements could be achieved. One route for improvement would be to increase the penetration of the hydrogen energy system to further reduce the demand for imported fossil fuels, balanced by a restriction on requiring significantly larger hydrogen energy system components. Alternatively, the number of wind turbines producing primary energy in the system could be reduced. This would reduce the capital cost of the project but could increase the station's demand for fossil fuels for electricity or thermal energy production. An estimation of the impact of reducing the number of wind turbines to two is presented in Table 8.15.

	System 2 FC + DEGS	
	3 turbines	2 turbines
Annual heat load in 2002 (MWh/year)	2020	2020
Annual electrical load from simulation (MWh/year)	1307	1307
Total user energy demand (MWh/year)	3327	3327
Excess electrical energy in system (from simulation) (MWh/year)	3545	1972
Extra excess electrical energy (secondary analysis) (MWh/year)	171.6	171.6
Total excess electrical energy (MWh/yr)	3716.6	2143.6
Available waste heat from model (MWh/year)	104	104
Total available heat energy (MWh/year)	3820.6	2247.6
Surplus heat energy		
rel. to 2002 load (MWh/year)	1801	228
rel. to 2002 load (% of total heat energy)	89.1	11.3
Heat load reduction required (% of 2002 load)	-89.1	-11.3
SAB consumption for thermal balance (L/year)	0	0
SAB consumption for electrical load (L/year)	120441	120441

Table 8.15: Comparative performance of System 2 when using 2 wind turbines.

The electrical energy output from three turbines at the station was calculated by the model as 4721 MWh/year (1573 MWh/year per turbine). 273 MWh/year of electricity is generated by the DEGS component using stored diesel fuel. 3327 MWh/yr of energy is directed to meet the total user demand for electrical and heating energy. 202 MWh/yr of energy is also consumed by the electrolyser for hydrogen production, but re-enters the energy system on demand as electricity generated by the fuel cell. The conversion efficiency of the storage system as a whole was therefore approximately 32%. The inclusion of waste heat captured from the fuel cell would improve this conversion efficiency slightly.

Under these conditions, 3717 MWh/year of excess electrical energy was available after meeting the electrical loads in the system. When combined with the waste heat captured from the FC and HEGS, 3821 MWh/year of excess energy was available to meet the station's thermal energy demand of 2020 MWh/year. A true surplus of 1801 MWh/year of energy was therefore available for other tasks.

If one turbine and its potential contribution of 1573 MWh/year of primary energy were removed, a net energy system surplus of 228 MWh/year would remain. This assessment is based on the crude assumption that the hydrogen storage system configuration specified for the three turbine system would operate in an identical manner with only two turbines. In reality, the removal of the turbine would result in a magnification of any demand for energy generation from the hydrogen system that compared to the three turbine system. Additional periods of demand for energy from the hydrogen system would also be likely. This would change the hydrogen storage sizing requirement and subsequently the size of the electrolyser component. The reduction in the rated capacity of the wind turbines would also be likely to result in demand for a large generation capacity from the fuel cell or HEGS. A larger FC component would subsequently increase parasitic hydrogen consumption from the component during idling mode, again impacting the hydrogen storage and generation components.

As an initial assessment, however, this analysis indicates that similar energy system performance could be achieved with respect to demand for imported fossil fuels if the turbine numbers at the station were reduced to two.

In summary, the installation of two wind turbines at Mawson Station and the inclusion of a hydrogen energy storage system could reduce the station's dependence on fossil fuels to 10-20% of the total user load. The hydrogen system would be similar in size to that developed for System 2 with three wind turbines, as detailed in Table 8.15.

8.4.3 *Considerations for specifying basic system design goals*

The combined results of Systems 1, 2 and 3 are presented for analysis in Table 8.16 below. Summaries of the basic characteristics and relative performance of the systems follow.

	System Results			Comparisons		
	System 1	**System 2**	**System 3**	S1 ~ S3 (% Δ)	S2 ~S3 (% Δ)	S2 ~ S1 (% Δ)
System goal for energy independence	100%	80%	100%			
Achieved system goal	Yes	Yes	**No**			
Diesel for electrical load (L/yr)	0	120441	0			
Diesel for heating load (L/yr)	0	0	59932			
Elyzer rated power (kW)	320	25	356	-10.1	**-93.0**	**-92.2**
FC rated power (kW)	399	85	100	299.0	-15.0	-78.7
HEGS/DEGS rated power (kW)	0	140	275	n/a	-49.1	n/a
Total gen capacity (kW)	399	225	375	6.4	**-40.0**	**-43.6**
H2 storage vol (m^3)	365	65	375	-2.7	**-82.7**	**-82.2**
Energy excess (MWh/yr)	1590	3549	1305	21.8	**172.0**	**123.2**
Energy excess %	29	70	24	5.0	46.0	-41.0
Electrolyser						
Elyzer output energy (MWh/yr)	2574	202	2801	-8.1	-92.8	-92.2
Consumption of system load (%)	47	4	52	-5.0	**-48.0**	**43.0**
Fuel Cell						
% time at idle / off	71	91	89	-18.0	2.0	-20.0
FC input energy (MWh/yr)	751	65	101	643.6	-35.6	-91.3
Contribution to energy input (%)	14	1	2	12.0	-1.0	13.0

Table 8.16: Comparative performance of Systems 1, 2 and 3 in achieving system goals.

System 1: a 100% energy independent system that achieved the nominated system goal, but used a very large hydrogen energy system with the most expensive and novel energy technologies (fuel cells). An increase in user load would critically compromise the station design and operating parameters.

System 2: an ~90% energy independent system that achieved the nominated system goal of 80+% independence for the electrical load. Required the largest volume of fossil fuels to support operations (~120,000 L/year for electrical load). – twice that required for System 3 – but used a significantly smaller hydrogen energy system. Compared to Systems 1 and 3, the electrolyser was ~90% smaller, the generation capacity ~40% smaller, and the hydrogen storage volume ~80% smaller. This would enable significant cost savings for the hydrogen system design that would compare well with the total system costs for Systems 1 and 2 when diesel delivery costs are considered due to the much larger sizes of those systems. The planned integration of fossil fuels and the availability of excess energy also offer advantages relative to the other systems. They include greater flexibility to meet increases in user load with excess energy or more fossil fuels, the potential to replace the FC component with a HEGS and cover the efficiency related deficit with fossil fuels or excess wind, and the possibility to operate the station with only two wind turbines.

System 3: an ~95% energy independent system that failed to achieve the system goal due to the need for ~60,000 L/year of diesel to meet a deficit in excess energy used for the thermal load. Used a system of comparative size to System 1, with a mixture of novel and conventional hydrogen conversion technologies. The smaller size of fuel cell compared to System 1 (25%) and the use of the HEGS would provide opportunities for cost savings but also consumed too much energy relative to the primary energy available from the wind turbines.

8.4.4 Impact of changing the user load and electrolyser efficiency

In addition to the basic system configurations presented above, the experiments also considered the operation of System 3 with variations to the electrical load, as per the results presented in section 8.3.4, but with a reduced demand for power from the electrolyser when idling. The revised electrical load values were 180 kW and 220 kW (200 kW +/- 10%). These loads were considered for electrolysers with different idle load ratings (EIL) of 40% and 10% of their rated power.

The results reveal a number of trends that link changes in the total system load and the size and performance of components, including (as the load increases):

1. All component sizes increase (except the wind turbines (WECS))
2. WECS contribution to energy production is constant, but the relative contribution (%) decreases.
3. Relative and absolute contributions of power from the HEGS and FC components both increase; this can be attributed to the increased load requirement and the increased capacity of the components resulting in a larger amount of energy produced during idle operation (for the fuel cell);
4. Total input energy production increases
5. Energy demand by the electrolyser increases in absolute terms and relative (%) terms, again due to increased demand for both idle operations and hydrogen production as a consequence of increased electrolyser capacity. The above analysis indicated that any increase in user load results in a magnified increase in electrolyser power demand.
6. As the electrolyser and user load consume more power, less excess energy is available for export (absolute and relative scales), even though the FC/HEGS are producing more input power (benefits are being absorbed by increased demand). For example, a 10% increase in load for the 200 kW load (40% EIL) system cuts the relative availability of excess power by half (24% down to 12% of total system power output). This can be attributed to the increase in electrolyser size (hence) demand being larger than the corresponding increase in generation capability.
7. Energy to user load increases in absolute terms (as expected) and in relative terms as less excess energy is available within the system.

Table 8.17 presents a summary of the size changes (% increase) for the key components, expressed in an alternate form of component size increases that result from nominal 10% increases to base loads of 180 kW and 200 kW. The data presented uses the modified results for the 40% EIL system that take into account assumptions for a 30% over-capacity for the electrolyser. This data illustrates the consistent correlation between electrolyser and storage capacity size changes, and the variation in the magnification factor relative to the 10% increase in load for these two components. It also illustrates the relationship between user load and total generation capacity, and the potential influence of large increases in electrolyser size.

The general conclusions to be drawn from this analysis of changing system loads are that changes in load result in proportional changes in component sizes – the electrolyser size and hydrogen storage capacity will adjust in unison with a magnification of the change to the station load. The magnification of the electrolyser/storage increase may be constant or compounded by the magnitude of the base load and/or the characteristics of the EIL; inadequacies in the model results that suggest a 30% over-capacity of FC size make this difficult to accurately determine. In addition, the generation capacities of HEGS and FC components will increase in close proportion to increases in user load, although additional size increases may be required if the electrolyser component size is significantly increased due to the idle power demands of the electrolyser. An increase in user load of 10% would therefore reduce the amount of excess energy available in the system by an amount greater than the load increase. These outcomes indicate that there are many motivations to pursuing improvements in energy efficiency to reduce or cap the station load at the current level (200 kW).

% increase in Component size	**180 kW load + 10%**		**200 kW load + 10%**	
	40% EIL	10% EIL	40% EIL	10 % EIL
Elyzer rated power (kW)	18.6	17 7	28	12.2
Total gen capacity (kW)	10	7.8	18	10.5
H2 storage vol (m^3)	18.9	16	31	13.9

Note: FC data for 40% EIL system includes correction to rated power of 30%.

Table 8.17: Impact of 10% increases in user loads on component sizes for System 3, 40% + 10% EIL

The impact of variations in the user load on the size of the hydrogen system components observed for System 3 using the 40% EIL electrolyser were also evident when the system used the 10% EIL component. As detailed in Table 8.17, an increase in user load resulted in a comparable increase for the total generation capacity and a magnified increase for the electrolyser rated power and storage volume. It is interesting to note that the increase in component size observed for the load increase to 220 kW for the 10% EIL system was approximately half that of the 40% EIL system. This indicates that the use of the 10% EIL had some positive benefit on the sizes of energy system components required.

Analysis of the initial design of System 3 (40% EIL) with a user load of 200 kW, and the performance of the system with the 10% EIL electrolyser indicates that the revised electrolyser enabled significant reductions in the sizing of all hydrogen system components. This included the electrolyser capacity (47% reduction), hydrogen storage volume (31%), and total generation capacity (36%).

Comparing the component sizes for the two electrolyser configurations when meeting the other electrical loads (180 kW and 220 kW) validated the impact of reducing the electrolyser idle load to 10%. It enabled comparable reductions in electrolyzer capacity, storage volume and total generation capacity to the results achieved with the 200 kW load system.

The reduction in electrolyser idle rating and the subsequent reductions in component sizes resulted in further changes to the total energy system performances. For the three user loads considered (180/200/220 kW), the following trends were observed when the 40% EIL component was replaced with the 10% EIL electrolyser:

1. Increased relative contributions (% of total energy input) of energy from the WECS components (6/7/9%) and the fuel cells (2/2/2%);
2. Increased availability of excess energy in relative (20/23/30% of energy input) and absolute terms (51/81/207% increase of MWh/yr).
3. Significant reductions (38-60%) in the absolute production of energy (MWh/yr) from the HEGS and FC components as a result of reduced component sizes;
4. Substantial reductions in the consumption of energy by the electrolyser in absolute (51/52/57% reductions in MWh/yr) and relative terms (22/25/32% of energy input). Put simply, over half the energy in a system with a conventional electrolyser (40% EIL) was used to operate the electrolyser for hydrogen production and idling activities and a reduction in the EIL to 10% cut the total system contribution to the electrolyser to only 25%. This resulted in an effective doubling of the available excess energy.

The reduction in electrolyser idle rating also influenced the specific operating characteristics of the energy system components. Through analysis of the operating hours of the 200 kW user load systems for the two electrolysers configurations, a reduction in the EIL to 10% was seen to have the following impacts:

1. Electrolyser hours of operation at idle reduced (6%) and hours at peak load (90-100% of rated power) were proportionally increased (6%). Therefore a reduction in EIL improved the utilisation factor of the component. For both systems, the electrolyser spent approximately a third of the time idling and two thirds of the time producing hydrogen at full capacity; each system spent only 8% of the year at alternative production capacities.
2. The fuel cells in the two systems operated for very substantial and closely comparable periods of time at idle (1% difference, ≈90% of operating hours). The remaining operating hours of operation were shared over the spectrum of 10-100% rated power, although the 40% EIL has already been shown to have an over-sized FC component (indicated by a lack of operation in the 70-100% power range). Therefore, a change in the electrolyser EIL can influence the FC component size but has little impact on the utilisation of the component. In both systems, the fuel cell component made a negligible contribution of power to the total system input, with this contribution reduced in the 10% EIL system due to the reduction in FC component size.
3. The HEGS component spent an increased amount of time at idle/off (7%), providing additional opportunities to reduce the parasitic consumption of hydrogen fuel relative to the 40% EIL system. This gain in time spent at idle was achieved primarily through a comparable reduction in the amount of time the component spent operating at full power (5% reduction), as indicated by the reduction in total operating hours of 647 hours. Therefore, variations in the EIL

can influence both the size and duty cycle of a HEGS component that is used as the primary alternative generation source to WECS. In both systems, the HEGS component spends approximately 15% of the year at power ranges between idle and 90% of rated power, indicating effective sizing of the component. The reduction in component size that resulted from the reduction in EIL produced a comparable reduction in the contribution of power from the HEGS (≈50%).

These observations generate the conclusion that improvements in the electrolyser performance can have a major impact on the necessary size of components – as the electrolyser requires less energy for idle operation, the wind and non-wind components can be smaller. Less stored energy is therefore used to run the electrolyser when it is at idle, and the HEGS/FC components also use less energy when at idle (lower rated capacity), resulting in a net reduction in demand for hydrogen storage. This can have a subsequent advantage on further reducing the size of the electrolyser rated power for adequate filling of the storage system, enabling additional reductions in component sizes. Also, these trends become more important as energy systems increase in size to meet larger user loads because of the absolute sizes of the components and the possibility of the magnified benefits from the use of an electrolyser with a lower EIL.

The EIL can also influence the utilisation/duty cycle of components, including the electrolyser and HEGS (when used as primary response). Reductions in EIL can therefore enable effectively duplicated reductions in unproductive hydrogen consumption in the system, achieved through reduced component sizes and more time spent off or at full capacity rather than at intermediate performance levels.

8.4.5 Utilisation of hydrogen storage

The capacity for hydrogen storage is an important element in any wind-hydrogen system. However, storing hydrogen is economically and energetically expensive. True optimisation of an energy system must include evaluation of the utilisation of the hydrogen storage component to determine if other energy storage mechanisms are more appropriate at some (or all) periods of time.

System 1 was the only system to specify and meet an energy system goal of 100% use of renewable energy. The hydrogen storage system consequently served a critical role in providing stored renewable energy when required. The system used a relatively large hydrogen storage capacity that was specified by the simulations as the minimum possible size needed to meet the annual demand for stored energy.

The graph of hydrogen storage pressure (c.f. volume) over the year for System 1 is presented in Figure 8.8. Analysis of the graph indicates that a large proportion of the storage volume (approximately 30%) is only used for a short period of time. The box on the graph between the time steps 5000 and 6000 hours highlights the lowest point of hydrogen pressure in the system, but this component of the storage volume is used for less than 10% of the year. Therefore, 30% of the storage system capacity must be purchased and installed but would be rarely used. This is a poor level of utilisation. Other forms of energy storage may be more appropriate for the short period of time that the under-utilised component of hydrogen energy storage is currently operating. However, to preserve the operating philosophy or goal of the station, any alternative energy storage technique would have to be capable of storing excess renewable energy resources. The replacement system would also exhibit poor utilisation and would need to offer cost advantages relative to the hydrogen system to justify the increased diversification to the energy system. Unfortunately, the options for long-term and cost-effective storage of electricity from renewable energy remain limited, hence the reason for this research into the use of hydrogen storage technologies.

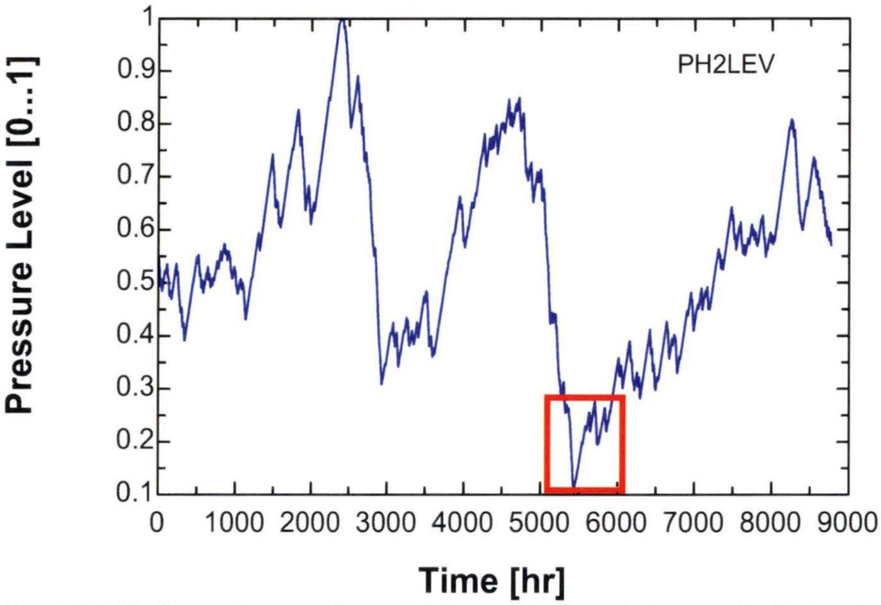


Figure 8.8: Hydrogen storage volume and demand for imported energy for System 1.

Improvements to the utilisation of the hydrogen storage volume could also be achieved through a change in the operating philosophy for the system. In the case presented, for example, the specified storage volume of 365 m^3 and poor system utilisation is a consequence of the system goal to achieve 100% energy independent operation. An alternative goal could be set for the system such as to optimise the utilisation of the hydrogen storage component and the penetration of renewable energy resources into the system. In System 3, this could enable a 30% reduction in the hydrogen storage volume. The size of the fossil fuel energy infrastructure would be configured to address only the peak period of demand on the hydrogen storage whilst achieving the maximum penetration of renewable and hydrogen energy resources into the system.

This alternate approach could also enable the improved utilisation of investments in other infrastructure at the station, such as the emergency power house (EPH). The EPH is an independent and parallel power generation system that can replace the main energy system when major faults occur and during annual maintenance. The EPH must be available on station and is best served using fossil fuels and conventional technologies as they are highly reliable and cost effective for the role. In addition to the existing roles, the EPH could interact with the wind-hydrogen system to replace the peak hydrogen storage capacity. The amount of energy content involved in replacing the hydrogen storage is not considerable, but replacing it with fossil fuels would have a dramatic impact on the total size of the hydrogen storage system and subsequent total system cost. Reducing the hydrogen storage size would also enable cascading size and cost reductions in related components such as the electrolyser, and potentially the fuel cells or HEGS components.

A comparison of the storage system utilisation for Systems 1, 2 and 3 (including the 10% EIL system) is presented in Figure 8.9. Both storage pressure level and filled storage volume are used to illustrate that either can be applied as an effective indicator of utilisation.

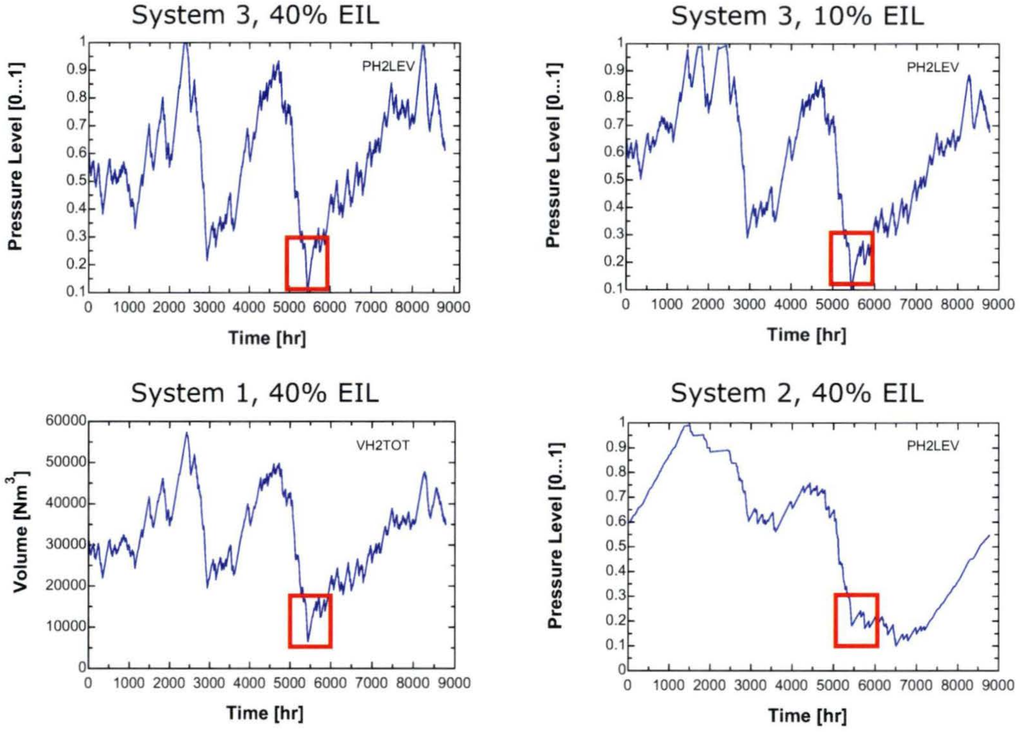


Figure 8.9: comparison of hydrogen storage system utilisation for Systems 1-3.

The figures illustrate that the characteristics of hydrogen storage utilisation identified for System 3 are common in designs where the system goal is preserved and changed in systems with alternative system goals.

For example, the System 3 result compares well with the utilisation profile for the same system design with an improved electrolyser idling load efficiency and with the profile for System 1. All the systems share a common goal of achieving 100% energy independent operation and have a component of storage volume that is poorly utilised in the 5000-6000 hours time-step.

In comparison, System 2 exhibits a similar but smoother profile for hydrogen storage utilisation that does not include an obvious component of under-utilised storage capacity. The minimum volume of stored hydrogen also occurs later in the year (during the 6000-7000 hour time-step). The goal for the systems allowed the use of imported diesel fuel to meet 20% of the station's electrical energy demands, clearly including the demand during the 5000-6000 hour time-step that was consumed from the hydrogen storage in Systems 1 and 3. The change in system objective enabled both a reduction (~80%) in hydrogen storage volume to 65 m^3 and improved utilisation of the expensive hydrogen storage component.

8.4.6 Impact of energy independence goals on the hydrogen storage volume

The energy system configurations presented above for Systems 1 and 3 specified the minimum component sizes needed to meet the station's electrical energy demands independent of fossil fuels. The design for System 1 was proven to also be adequate to meet the total station energy demand without reliance on fossil fuels. The design presented for System 3, however, did require imported fossil fuels to meet the station's thermal energy demands. This indicated that aiming for 100% independent operation of the electrical system was an over-ambitious goal as the station was still dependent on fossil fuels in some capacity. The results of System 2 illustrated the benefits of specifically aiming for some component of electrical energy use to be met using fossil fuels, including significant reductions in the capacities of all hydrogen energy system components. The above analysis of storage utilisation discussed the potential benefits of using existing fossil fuelled infrastructure such as the EPH to meet a part of the station's energy demand and subsequently improve storage utilisation and reduce component sizes.

Based on these results, the sensitivity of the hydrogen storage volume to the system's energy independence goals was evaluated for Systems 1 and 3. In contrast to the goal for System 2 (20% dependence on fossil fuels for electricity generation), this analysis investigated the potential reductions in hydrogen storage volume that could be achieved with minor dependence on fossil fuels.

The results are detailed in Table 8.18. They are expressed as the proportion of an average year that the station could operate independent of fossil fuels, assuming all other system parameters remained consistent with those originally specified for Systems 1 and 3. The results were calculated via simulation as the amount of imported energy needed to meet the station's electricity needs when the hydrogen storage volumes were reduced. A graph of the energy import requirements relative to hydrogen storage volume is presented in Figure 8.10.

Extent of station operation independent of fossil fuels	Hydrogen storage Physical size @ 200 bar pressure	
	System 1: FC only	System 3: FC + HEGS
100% of year	365 m3	375 m3
99.5% of year	325 m3 (approx)	335 m3 (approx)
99% of year	295 m3 (approx)	305 m3 (approx)

Table 8.18: Analysis of hydrogen storage volumes and energy independence of station operations.

The volumes of hydrogen energy storage required to operate the station for 99% and 99.5% of a year were calculated by converting the annual percentage figures of 'non-hydrogen fuelled operation' to amounts of imported energy needed to power the station for that time period. As illustrated in Figure 8.10, the energy import values were then correlated with the relevant hydrogen storage volume for each system configuration, as determined by simulation.

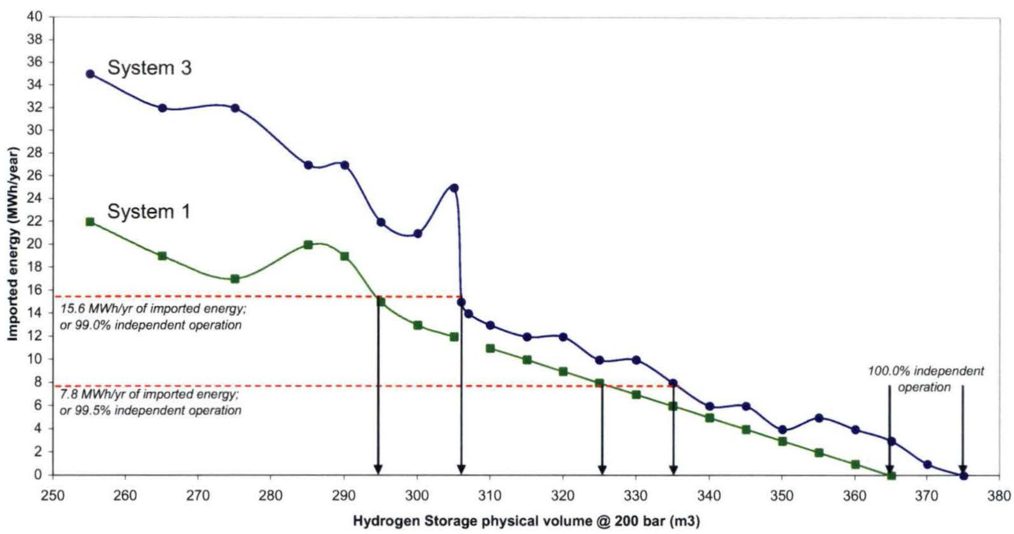


Figure 8.10: Sensitivity of hydrogen storage to demand for imported energy for Systems 1 and 3.

The results indicate that even minor concessions towards a goal of 100% energy independent operation for the station's electrical energy demand can have significant impacts on the volume of hydrogen storage required. For example, using fossil fuel energy for only 0.5% of the year enabled an 11% reduction in storage size for Systems 1 and 3. Similarly, using fossil fuels for 1% of a year enables a 19% reduction in hydrogen storage volumes for both systems.

Based on these results, the policy of not depleting the level of hydrogen stored to below 10% of the total stored volume could also be modified as the system would have a 'safety net' of stored energy available in the fossil fuel energy system. This would enable further reductions in the size of the hydrogen storage system.

The results for both systems do exhibit aberrations to the generally linear relationship between storage volume and dependence on imported energy resources, with peaks occurring at storage volumes of around 300 cubic meters. At the specific volumes considered, the relationship to dependence on imported energy changes with a significant increase in demand for fossil fuels occurring with only a minor reduction in storage volumes. Even smaller storage volumes, however, require less imported fossil fuels. The return to a linear relationship between volume and independence after the peak suggests that the result is an artefact of the simulation calculations, perhaps relating to on-off switching of components, or a complication of the specific sizes specified for components in the simulation. The general operation of components in the real would most likely not produce such peaks. The step change increase in the demand for imported fuels seen for System 3 for hydrogen storage volumes smaller than the peak (relative to volumes larger than at the peak) is interesting and could be worth further investigation, but the general trend for both System 1 and System 3 is that the demand for imported energy increases as the stored hydrogen volume decreases.

8.4.7 *Impact of system design and operation parameters on the efficiency of the hydrogen energy storage system*

The 'round trip efficiency' of an energy storage system, or the proportion of energy that can be effectively supplied relative to the amount of energy that must be fed into the system, is one measure of the performance of any energy system. The efficiency will influence the amount of primary energy needed to 'charge' the storage system and the storage capacity required to deliver a specified amount of energy to the user.

The three energy system designs and variations to individual component performance or system goals studied in this research provided an opportunity to assess the efficiencies of different hydrogen energy storage configurations. Table 8.19 presents a comparison of the hydrogen energy storage system efficiencies for the configurations of Systems 1, 2 and 3 reviewed in the preceding sectionsIt also includes the result for System 3 when using an electrolyser with a 10% idle load. In all cases, a peak electrical load of 200 kW is assumed. The hydrogen system efficiency was calculated as the amount of electricity produced by hydrogen-fuelled components (FC and HEGS) relative to the electricity consumed by the electrolyser in producing the hydrogen. As specified previously, all system configurations required the balancing of the volumes of hydrogen stored at the start and end of a year, enabling this type of simple but effective 'energy out/energy in' calculation.

	System 1	System 2	System 3	System 3
	40% EIL			10% EIL
Electrical energy independence	100	80	100	100
FC energy supply (MWh/yr) HEGS energy supply (MWh/yr)	751 n/a	65 n/a	101 589	62 249
Elyzer energy use (MWh/yr)	2574	202	2801	1359
H2 system efficiency (%)	**29.2**	**32.2**	**24.6**	**22.9**
FC + HEGS contribution to system power (%)	14	1	13	6
Elyzer consumption of system power (%)	47	4	52	27

Table 8.19: Hydrogen energy storage system efficiencies for Systems 1-3.

As presented in Table 8.19, System 2 exhibits the highest system efficiency. This is due to the use of only a fuel cell for conversion of hydrogen to electricity and support of the hydrogen system with fossil fuels for 20% of the electrical energy demand. The fuel cell was proven to convert hydrogen to electricity more efficiently than the HEGS components, providing an advantage over systems that use HEGS. Using fossil fuels allowed a smaller hydrogen storage system and improved the utilisation of the installed hydrogen storage capacity. The full impact of the size reduction is illustrated by the electrolyser's consumption of only 4% of the total electricity available in the system for System 2, as compared to ~50% for Systems 1 and 3 when using a similarly performing electrolyser.

System 1 has the second highest efficiency based on the use of an efficient fuel cell component for hydrogen conversion, as per System 2. However, the goal of achieving 100% energy independent operation for this system requires a significantly larger hydrogen energy system that has a greater proportion of poorly utilised capacity (to meet peak loads) which reduces the system efficiency.

System 3 exhibits the poorest system efficiency due to the use of the less efficient HEGS components for electricity generation from hydrogen, and the need to have sufficient storage capacity to enable 100% energy independent operation for the station.

These results are all as expected. The results for System 3, however, are unexpected when the electrolyser with 10% idling load is utilised. Given the performance of System 3 relative to the other systems when all used electrolysers with 40% EIL, it is understandable that the system continues to perform poorly when using the alternate electrolyser. However, the alternate electrolyser consumed less power during non-productive operation and should have resulted in performance improvements with the same system design compared to operation with the 40% EIL electrolyser. This outcome is not indicated in the results presented in Table 8.19. The discrepancy can be explained through analysis of the efficiency of the hydrogen conversion components (FC + HEGS) used in both versions of System 3. As presented in Table 8.20, the 10% EIL version made less effective use of the stored hydrogen when generating electricity. The efficiency of conversion of the individual components and their combined (proportional) conversion efficiency was lower in the 10% EIL version. This negatively influenced the total hydrogen storage system performance, outweighing the benefits gained through use of a more efficient electrolyser.

	System 3	
	40% EIL	10% EIL
Electrical energy independence (%)	100	100
FC contribution to H2 electricity output (%)	14.6	19.9
HEGS contribution to H2 electricity output (%)	85.4	80.1
FC conversion efficiency (kWh/Nm3)	1.54	1.50
HEGS conversion efficiency (kWh/Nm3)	1.14	1.08
Combined FC-HEGS efficiency (kWh/Nm3)	**1.20**	**1.16**

Table 8.20: Efficiency of HEGS and FC components in System 3 (40% / 10% EIL).

The comparison of Systems 1 and 2 illustrates the gains in hydrogen storage efficiency that can be accessed through changes to the system goals. In this case, altering the goal with regards to energy independent operation and allowing some component of fossil fuel use yields a small improvement in the efficiency of the hydrogen system. The comparison of Systems 1 and 3 illustrates the advantages of using only fuel cell components for hydrogen conversion to improve the total system efficiency. However, as discussed previously, the selection of components must also consider other issues such as capital cost and the less efficient HEGS have advantages in this regard.

The analysis of the impact of electrolyser design on the performance of System 3 indicates that changes in a system component can yield positive results by one measure but also alter other aspects of system behaviour to yield negative results in other areas of performance. This illustrates the importance of considering multiple factors in the system design. For example, the poorer storage system efficiency that resulted from the use of the 10% EIL electrolyser in System 3 must be tempered by the 30-47% reductions in component sizes and approximate doubling of available excess energy that also occurred (from 1369 MWh/year to 2366 MWh/year). Whilst having a negative impact of reducing the storage system efficiency, the alternative electrolyser actually enabled the system to perform far better overall and achieve the system goal of energy independent operation that had not been possible with the 40% EIL component.

8.4.8 Impact of load profile selection on the modelling results

Considerable effort was invested during the preparation phases of the modelling process to develop load profiles for the simulations that would accurately reflect the energy demands of Mawson Station. The limitations of the modelling toolbox were considered in the development of a modelling strategy. The main limitations were that the model only accepted a single load profile and the energy flow calculations did not consider the potential for combined heat and power (CHP) operation of components such as the HEGS or FC.

The modelling strategy used two load profiles – a practical load that included only the electrical energy demands, and a conservative load that included the thermal and electric energy demands, with the heating loads manually forced to occur during periods of known peak wind speeds. Comparison of the two profiles illustrates the importance of developing realistic modelling strategies and accurate load profiles.

The majority of the simulation activities focused on the use of the practical load profile. The use of this profile produced a viable set of energy system configurations that were capable of meeting the electrical energy demands of the station with optimised sizes for the hydrogen storage components. Less precise calculations were conducted for thermal demands based on annual and monthly performance of components. This allowed a broad analysis of the viability of the systems to meet thermal loads but higher resolution and automated analysis would improve the accuracy, efficiency and ease of the process.

The conservative load profile was based on the assumption that excess wind energy could be used to meet the thermal energy demands for the majority of the time if the load were forced to occur during periods of the day when excess wind was expected to occur. Analysis of the wind data indicated that wind peaks occurred over the midnight period on 72% of evenings. However, during periods when excess wind energy was insufficient to meet the larger than realistic user load, the hydrogen energy system was to be used to operate the system. The load was larger than realistic due to the forcing of 24 hours of thermal loads into a 12 hour period.

The outcome of the conservative profile was a significant over-sizing of the hydrogen energy system components compared to the system configuration presented for System 3 when using the practical load profile. This was directly attributable to the larger user loads specified for the simulations. When compared to the closely examined and viable results developed using the practical load profile, the conservative load profile was shown to 'recommend' a highly conservative energy system design that was significantly larger than realistically required. The approach did not take into account the capability to capture waste heat from the FC and HEGS or the greater ability to defer heat loads over time – instead all loads were met unnecessarily using the hydrogen system.

As a consequence of these initial outcomes, the conservative load profile was deemed to be an unrealistic representation of the station load and not an effective mechanism for simulating the true CHP energy generation capabilities of the energy system. No further simulations were undertaken using the conservative load profile.

8.4.9 Analysis of modelling tools and methods

In addition to evaluating the integration of three hydrogen energy storage systems into Mawson Station's energy infrastructure, the experiments also aimed to assess the performance of the models and modelling tools that were used.

The most important measures of performance included:

1. The viability of using the existing energy system models to represent the energy system of Mawson Station
2. The skill levels required to use and modify the models and tools, and the functionality that could be achieved by non-expert users.

The expected viability of the models and modelling tools used were key factors in their selection. As discussed previously, there was a high level of technical similarity between the energy systems used at Mawson Station and the facility upon which the models were originally developed (Utsira Island, Norway). The major constraint to applying the models to the Mawson energy use scenario was expected to be the inability of the models to simulate the combined heat and power (CHP) energy system at Mawson.

A strategy was developed to address this lack of CHP capability through the use of two load profiles (practical and conservative) and the two-stage analysis of electrical and thermal loads as required. The results indicate that the use of the practical load profile was an effective and viable method of simulating the CHP capability of the station. The tools packaged with the model enabled the necessary actions for post-simulation analysis to assess heating loads and quality-assure the results from the model. Although the results could not be as accurate as those that would be produced with an integrated CHP wind-hydrogen model, the approach is deemed to be viable based on the performance of the models with the practical load profile and two-stage analysis technique. The conservative load profile was not viewed as an effective representation.

One undesirable feature evident in the modelling toolbox that did not significantly influence the viability of the models to represent that Mawson energy system, but did have a minor impact the accuracy of the results. The problem related to the over-sizing of fuel cell components in various circumstances by up to 30%. Analysis of the component performance after the simulations indicated that the upper proportions of the fuel cell capacities were not utilised by the energy system during some simulations, yet re-running the simulations with smaller (or corrected) component sizes compromised the simulation. Corrections were made where possible to the fuel cell sizes presented in the results, but this over-sizing would have resulted in some over-sizing of other components such as the electrolyser. Identifying and correcting this secondary over-sizing was not possible through post-simulation analysis, but the impact of not making such corrections was judged to be insignificant to the results.

Revising the model to avoid this unreasonable behaviour proved to be beyond the user's capabilities, illustrating one of the major weaknesses in the model relative to the second measure of performance for the modelling tools – the skill levels required to use and modify the models.

Prior to commencing the experiments associated with this research, several months were invested to develop familiarity with the modelling software and the specific energy system models that had been developed by Ulleberg. The skills and knowledge needed to use the pre-existing model to simulate Mawson's energy system without further input or supervision by modelling 'experts' were developed to a sufficient level. This included understanding the modelling software and the computational processes involved, understanding the user interface and analysis tools, developing modelling strategies that would enable the models to be applied to the Mawson design, producing data files of an appropriate format for the model, and interpreting the results from the model.

The skills developed did not include the creation of new components for inclusion in the energy system model and the compiling of collections of components into specific models. Through discussions with the model developer (Ulleberg), it was determined that such skills would have been needed to correct the fuel cell-related fault in the existing modelling. To stop the over-sizing of the fuel cell components, new 'control system' components would need to be developed (based on the existing algorithms) for each of the system designs. The control systems would make due consideration of the unique interactions of wind resource, user loads and hydrogen storage system activity for the Mawson Station scenario. The changes to the control systems, relative to those in the existing models, may only have needed to be small, but could have had a significant impact on the operation of the model. The user's skills with the model and tools were adequate to identify the fault and engineer a compromised solution, but were not sufficient to fully correct the issue.

This outcome indicates that some constraints exist when applying the HYDROGEMS energy system models to other projects even if strong technical similarities exist with the original or source project. The result also indicates that significant levels of skill need to be developed with the modelling tools to enable the creation of accurate energy system models as a foundation for executing simulations and assessing energy system designs.

The application of the pre-existing models to the Mawson energy system was the first attempt to transfer the tools to another energy system and the fuel cell fault could not have been predicted. The experiences gained through completing the experiments for this research and the associated results remain relevant to the assessment of the tools' performance. The success of the experiments in investigating a number of designs and variations in parameters, evaluating and interpreting results, and identifying issues in result quality, indicate that the HYDROGEMS modelling toolbox offers a high level of functionality and capability for models that work without flaws. The skill level required to execute and evaluate the simulations, therefore, is markedly lower than that required to develop the original models.

This final observation and personal experiences with the modelling process support the use of a multi-stage approach to developing and executing simulations of hydrogen energy systems. The approach would optimise the contributions of skills and labour of 'expert' and 'general' energy system modellers for projects. The proposed stages include:

1. An expert in energy system modelling uses appropriate skills and tools to develop models for specific energy use designs and scenarios, including quality testing with representative system configurations. For example, the hardware of System 1 with a control system tailored for Antarctic stations.
2. The expert specifies the formats and quality control parameters for the data files that are to be used in the models, which are then be prepared by general users or by the expert.
3. The expert validates the quality of the data files and confirms the operation of the models using the data files and the representative system configurations.
4. The expert compiles the models and data files into discrete packages that are certified only for use with the specific projects. These packages allow general users only limited ability to vary parameters in the models, and include structured formats for the presentation and analysis of results.
5. General users can then execute the models with the necessary variations in parameters and conditions. Results are interpreted using guidelines developed by the expert to allow informed analysis of the system designs and confirmation of the integrity of the results. Issues with the results, such as the fuel cell-related fault in these experiments, can be addressed by the modelling expert.

The use of Ulleberg's pre-existing model in these experiments provided a practical test (and developing ground) for this multi-stage process. The models were produced and tested by an expert, data files were produced to specifications provided by the expert, and executions were simulated using a model package with reduced functionality. The result presentation and analysis tools were utilised to interpret the results and conduct critical quality testing. The faults identified with the control system could be efficiently corrected by the expert, and the package redeployed for further use by general users.

In practice, general users would need less knowledge and skill than that developed for this research but would also have less capability to assess the results and understand the limitations of the model. For the purpose of this research, however, it was necessary to develop a skill set that 'straddled' the divide between experts and general users of energy system models.

Therefore, if the multi-stage analysis process was used for future applications of the HYDROGEMS toolbox and Mawson models, the skill levels required for operation by non-expert users would be reasonable. A suitably packaged tool would conceivably enable a new user to execute and analyse a limited range of simulations in a very short period of time (in the order of hours). The tool would require additional structure and instructions to those currently included in the HYDROGEMS toolbox, but this content could be developed based on the analysis techniques and methodology used in this thesis. The skills required to modify the models, however, remain in the domain of energy system modelling experts and their development would require months or years of effort.

Although the viability of applying the modelling tools to Mawson Station was proven to be viable when using the practical load profile, opportunities remain to improve the performance of the energy system models.

Specific areas where improvements to the model design or process would be beneficial include:

1. *The simulation of combined heat and power (CHP) systems*;
   As noted previously, more detailed and integrated modelling of the heat and power loads of energy systems such as that used at Mawson Station would improve the accuracy of results, potentially enabling reductions in the specified sizes of the hydrogen energy systems. Such models (and CHP technologies) could also be utilised for systems in other environments with large heating loads.

2. *Using multiple components*;
   The existing models use single units for the hydrogen system components, although multiple units of each component would often be installed in practice. Extending the models' capability to specify multiple units of components such as HEGS, FC, or electrolysers and independently control their behaviour would improve the relevance of the models to practical situations and potentially reduce the recommended size of components. For example, the ~400 kW FC used in System 1 could be served with 4x 100 kW units, with some units set to turned off rather than idling (and consuming hydrogen fuel) when not required.

3. *Automated optimisation process*;
   Several thousand simulations were conducted simply to optimise the system configurations. An automated process based on the manual assessment technique would reduce the time required to specify system designs.

8.5 *Energy system modelling conclusions:*

The experiments presented in this chapter aimed to address three objectives relating to the use of computer modelling tools and the specification of wind-hydrogen energy system designs for Mawson Station in Antarctica. Several thousand energy system simulations were conducted using the HYDROGEMS modelling toolbox and three pre-existing models of energy systems that included hydrogen energy technologies. The simulations used historical data relating to Mawson Station's operations over the past fifty years and recent market assessments of hydrogen energy technology capabilities.

Although a number of assumptions and compromises were required due to the practical reality of the station's energy system design and the capability of the modelling tools, the three objectives were achieved:

1. Three energy system designs were assessed as viable configurations for operating Mawson Station with wind and hydrogen energy technologies and suitable operating parameters were specified, including one system capable of operating with zero dependence on imported fossil fuels.
2. The viability and impact of making changes to several key elements of the energy systems' operations were assessed and subsequent recommendations presented for the selection and operation of hydrogen energy systems.
3. The three energy system models used in this study were all shown to be viable representations of the integration of hydrogen energy storage technologies into the existing energy system of Mawson Station. The useability of the modelling tools, however, was shown to be critically constrained by the expert knowledge required to construct and quality-assure an energy system model. A two-stage process of developing and utilising energy systems was subsequently proposed to optimise the labour contributions of expert and non-expert users to create and apply such models.

The most important outcome from the experiments, considering the broader objectives of this thesis, is the validation of the technical possibility to operate Mawson Station using any of the three different hydrogen energy systems considered. The size of the hydrogen system and the amount of fossil fuels needed would depend on the design and operating parameters of the system and components, the goals of the system with respect to energy independence, and the size of the user loads.

The wind-hydrogen energy system designs that were evaluated are:
System 1: a wind-H2 system using only a fuel cell (FC) for hydrogen conversion.
System 2: a wind-H2-diesel system using a fuel cell for stored energy conversion, assisted by a conventional diesel-fuelled electric generator (DEGS);
System 3: a wind-H2 system that used a single FC and a conventional electric generator configured to operate on hydrogen (HEGS) for hydrogen conversion.

For each of the energy system designs considered, several general characteristics can be summarised relating to their system size and operating parameters.

1. *System 1* would require a relatively large (and expensive) hydrogen energy system that used a large fuel cell for hydrogen conversion to electricity. The

design would enable the station to operate completely independent of imported fossil fuels, but would be vulnerable to changes in user load.

2. *System 2* would require a hydrogen energy system significantly smaller than that specified for Systems 1 and 3, but continue the station's reliance on imported fossil fuels for the station's electrical energy demands. Approximately 120,000 L of diesel per year would be needed to augment the wind energy resources. Sufficient excess energy would be available from the system to meet all of the station's thermal energy demands without further use of fossil fuels. The system would subsequently have an ~10% dependence on imported fuel. Preliminary analysis suggests that the excess energy may be sufficient to allow the use of only 2 wind turbines without requiring significant changes to the system design or station operation.
3. *System 3* would require a similar sized energy system to that used in System 1, but include a HEGS component for electricity generation from hydrogen. This use should reduce the total cost of the system (relative to System 1) and reduce the challenges associated with finding serving infrastructure etc. However, the poor efficiency of the HEGS compromises the system's ability to operate fully independent of fossil fuels. Approximately 60,000 L of diesel per year would be needed to meet the station's thermal energy requirements.

These characteristics are dependent on the operating parameters of the station remaining consistent with those specified in the simulations, including the use of three wind turbines and the size and profiles of the thermal and electrical loads.

In addition to assessing the use of hydrogen energy systems at Mawson Station, the simulation tools were also applied to investigate specific aspects of system operations. Issues included variation to the user load, changes to the electrolyser power demand at idle, selection of the hydrogen conversion components, utilisation of the hydrogen storage capacity and sensitivity to the system goal for energy independence, and the efficiency performance of the hydrogen storage system. The key outcomes include:

User load: A peak electrical load of 200 kW was specified for most simulation conditions, based upon current demand at the station. However, changes (particularly increases) in energy demand often occur with variations in activities, installed equipment and populations at the station. Simulations were executed using System 3, aiming for 100% energy independent operation for the electrical load, to evaluate the impact of load variations. The results indicated that an increase in the user load (of 10%) resulted in comparable or magnified increase in the size of the hydrogen energy system components and subsequent reductions in the availability of excess energy in the systems. In cases such as System 1, an increase in the load would critically compromise the station's ability to meet the operating parameters (e.g. independent of fossil fuels). If an increase in energy consumption at a station could not be avoided, it would be preferable to schedule new/additional loads during current periods of low demand. This would result in a flatter load profile but not increase the peak demand and mitigate the impact of the load increase on the size changes required for the hydrogen energy system components.

Electrolyser idle load: The electrolyser components used in the systems seeking 100% independent operation consumed substantial proportions of the total available energy reserves to produce hydrogen. The operating hour statistics of the components, however, indicated that they functioned in idle mode for large proportions of the year. During these periods, the electrolysers consumed electricity equivalent to 40% of their rated power – a significant 'parasitic' load in the energy systems given the large capacity of the electrolyser components. These parasitic loads impacted the sizes of the fuel cell and/or HEGS components and the availability of excess wind energy in the systems. Simulations were executed to assess the impact of improving the performance of electrolyser components during idling mode to consume only 10% of their rated power. The variation enabled a significant reduction in the size of all hydrogen energy system components in a number of situations. Individual size reductions for System 3 configured for a 200 kW practical load, for example, ranged from 11% (fuel cell) to 47% (electrolyser), with an average reduction over the four key hydrogen system components of 34%.

The results indicated that significant benefits could be gained in the cost and performance of hydrogen systems by reducing the idle power demand of electrolysers. Two approaches were suggested to achieve this - creating operating protocols that enabled conventional electrolysers (40% EIL) to reduce their effective power consumption during idling (such as by switching off) or the development of continuously operating components that operated more efficiently when idling (consume less power).

Hydrogen conversion components: the conversion of stored hydrogen into useful forms of energy, particularly electricity, is obviously a critical capability for any hydrogen energy system. Two forms of conversion technologies are generally considered for this role – fuel cells and converted combustion engines (HEGS) – with relevant advantages and disadvantages for each. Fuel cells are known to be more efficient at converting hydrogen to electricity yet are less commercially mature and significantly more expensive. In contrast, HEGS are relatively cheap and more readily available and supported by conventional infrastructure, but are less efficient at converting hydrogen fuel to electricity.

The experiments evaluated the performance of both components and the potential impact of their inclusion in energy systems. The results confirmed the efficiency advantage of fuel cells with a 25-34% gain in energy produced per unit of stored hydrogen compared to HEGS components (1.14 kWh/Nm^3). These gains, however, were achieved through the use of large (85-400 kW) fuel cell components. Although economic costs were not considered in this study, extrapolation of data from relevant documents such as the recent H-SAPS study indicates that fuel cells of this size would be prohibitively expensive [10]. HEGS components would be more economically accessible to Antarctic communities and better suited to existing operations, experience and supporting infrastructure. The inclusion of the less efficient HEGS components in systems, however, does have broader impacts than the efficiency of converting stored hydrogen and the cost of components. For example, comparison of the results for Systems 1 and 3, illustrated that the inclusion of a HEGS component increased the sizes of other system components and consumed more net energy in the operation of the hydrogen storage system. The consequence of the inclusion of a HEGS in System 3 was the ultimate failure to meet the system goal of 100% energy independent operation. System 1, operating under similar constraints but only using a fuel cell, had (because of that FC's efficiency) sufficient excess energy available to meet the thermal loads of the station without importing fossil fuels. The use of the cheaper HEGS component in System 3 may have resulted in a higher total system cost or unacceptable performance characteristic (need for fossil fuels). The selection of hydrogen conversion components must therefore consider the full impact of the component's performance on the system as a whole, including technical elements (system sizes, need for fossil fuels) and non-technical issues (maturity of the technology, ability to access service facilities, total system cost).

Storage utilisation: Hydrogen storage technologies are relatively expensive when compared to the storage of liquid fuels (e.g. diesel) due to the materials used and physical sizes and high pressure capabilities needed to store gaseous fuel. Making effective use of the hydrogen storage component is therefore an important consideration in designing hydrogen energy systems. The experiments assessed the degree of utilisation of the hydrogen storage component of an energy system designed to meet 100% of the station's electrical energy demands using wind and hydrogen energy (System 3). The results indicated that approximately 30% of the storage volume was highly under-utilised, seeing service for less than 10% of the year.

The proportion of poorly utilised capacity, however, was reduced for systems that used fossil fuels to meet part of the station's electrical energy demand. In such cases (System 2), the stored fossil fuels effectively replaced the demand from the hydrogen storage during the period when the under-utilised component was otherwise called into service. In addition to improving the utilisation of the hydrogen storage, the fossil fuels also enabled a reduction in the size of all the hydrogen energy system components. Comparing the results from System 2 with System 3, for example, the planned use of fossil fuels enabled an ~40-90% reduction in the size of the electrolyser, generating capacity, and storage components. System 2 consumed twice as much diesel fuel per annum to meet the station's total energy demands (thermal and electrical), with an ~ 10% dependence on imported energy. System 3, with a much larger system and poorly utilised hydrogen storage, remained dependent on fossil fuels for the thermal energy demands with a net dependence on diesel of ~5%. The obvious advantages of System 2 were achieved, in part, from the cascading efficiency gains that were derived from not needing to fill an under-utilised proportion of the hydrogen storage.

Optimising the utilisation of hydrogen storage, therefore, can have direct benefits on reducing the size of the storage reservoir but also reduce the overall hydrogen system size. Improvements to the utilisation can only be achieved, however, by replacing the storage capacity with some other form of energy storage. Fossil fuel systems are viable low cost alternatives for long-term storage of energy that could fill such a role, but have other disadvantages (cost, environmental impact, security of supply etc). A suggested approach to maximising the utilisation of all infrastructure at the station, including the hydrogen energy storage system, is the use of the mandatory Emergency Power House (EPH) facility to replace the under-utilised hydrogen storage capacity. This would maximise the use of all critical investments and minimise the installation of additional storage capacity (hydrogen or otherwise).

Storage size sensitivity: Initial results from the experimental program indicated a general performance advantage, particularly the need for smaller hydrogen system components, for energy systems that included some component of fossil fuels to meet the electrical energy demands of the station. The results from the hydrogen storage utilisation experiment further highlighted the benefits that could result. As a consequence, the impact on the hydrogen storage component size (or 'sensitivity') of small dependencies on fossil fuels was assessed. The results indicated that even minor concessions towards a goal of 100% energy independent operation for the station's electrical energy demand could have significant impacts on the volume of hydrogen storage required. For example, using fossil fuel energy for only 0.5% or 1% of the year enabled 11% and 19% reductions in storage size (in both Systems 1 and 3).

Combining the results from the utilisation and sensitivity analyses, the planned inclusion of a small contribution by imported fossil fuels towards the total energy demand of a station can result in significant reductions in the size of hydrogen system components and improvements to the utilisation of hydrogen storage. Again, the fossil fuel-based contribution could be met using infrastructure that was also required for other critical tasks (e.g. the EPH), providing opportunities to improve the utilisation of all energy system infrastructure.

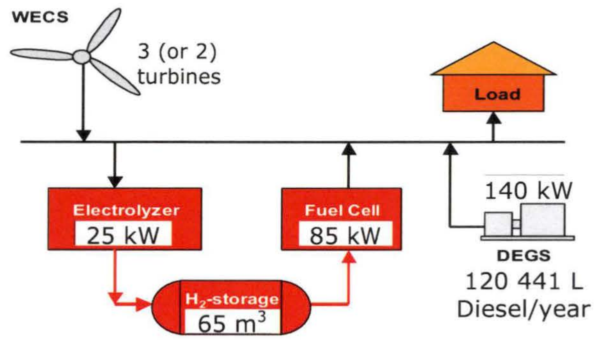
Storage system efficiency: A critical component of all of the energy systems considered was the ability to store excess renewable energy (through the generation of hydrogen) and subsequently release that energy on demand. As established by the 1st and 2nd laws of thermodynamics [12], some component of energy loss must occur during the storage and release process. The research provided an opportunity to evaluate the practical efficiency of hydrogen storage systems, measured in terms of the energy produced relative to the energy consumed in charging the system. This considered the operation of the electrolysers, storage capacity and electricity generation components (HEGS and/or FC) specified for each of the three systems (for a 200 kW electrical load).

The experiments revealed that the hydrogen energy systems considered had a 'round trip' efficiency of approximately 25-33%, influenced by the components used and the size of the systems. This represents a high proportion of 'lost' energy from the storage systems and illustrates why improvements to the electrolyser performance or utilisation of storage capacity can have such a significant impact on the total system performance. The results also suggest that the use of energy from hydrogen storage should be minimised where possible as it effectively requires three to four times as much primary energy to meet the load. Therefore, in an energy system where the primary energy inputs are variable (e.g. wind energy at Mawson), loads should be scheduled when ever possible to be serviced directly by the wind-generated energy. In the case of Mawson, this would require a greater focus on demand management.

The experiments also indicated that the hydrogen system efficiency is not a good critical measure of the overall hydrogen system performance. Changes to the system's design and operation that yield significant overall benefits, such as enabling smaller component sizes, may not be exhibited as improved hydrogen system efficiency (e.g. System 3 with an electrolyser with 10% idling load). Therefore, understanding the net efficiency of a hydrogen system is important for making broader system strategies (e.g. pursue demand management) but the efficiency should not be used as a key measure of optimised system design.

8.5.1 Recommended energy system for Mawson Station

The initial results from the modelling for the three energy system designs, coupled with the outcomes from the secondary analyses, indicate that System 2 is the best suited energy system design for Mawson Station, as presented in Figure 8.11. The system is capable of meeting the station's thermal and electrical energy demands with a total requirement for ~120,400 L of diesel fuel per year (equivalent to an ~10% dependence on imported fuels).



System 2: Wind / Electrolyzer / Hydrogen Storage System / Fuel Cell / DEGS

Figure 8.11: Recommended system configuration for Mawson Station (System 2).

This recommendation for System 2 is based on several factors:

1. The hydrogen energy system specified is substantially smaller than that required for the other system designs – this represents a significant cost saving for the initial development of the system.
2. The design maximises the utilisation of the hydrogen storage component.
3. The availability of excess energy in the system after meeting the annual thermal and electrical loads provides an opportunity to reduce the number of wind turbines installed. Alternatively, the excess energy could be used to generate hydrogen for other tasks (e.g. supporting vehicles or field camps) and/or the hydrogen system size could be nominally expanded to reduce the diesel demand further.
4. Existing energy infrastructure such as the diesel power house could be used in the design, providing an effective and efficient transition pathway. The existing diesel generators (DEGS) could be used for power generation from diesel or converted to operate with hydrogen fuel. The fuel cell included in the design for System 2 could be replaced with a HEGS component without significant impact on the system performance. The excess wind energy available in the system when 3 turbines are installed could be used to offset the efficiency losses associated with the replacement of the fuel cell.
5. The design also allows further advantages for the smooth introduction of new technologies as the smaller hydrogen systems could be installed initially to develop experience and knowledge. As existing assets reach the end of their service lives and/or hydrogen technologies become more economically competitive, additional components could be installed to increase the capacity of the hydrogen energy system.

6. The system design provides opportunities to maximise the investment in 'parallel' energy system infrastructure such as the Emergency Power House, which could be used for the DEGS power generation.
7. The inclusion of known technologies in the design and the relative ease with which additional fossil fuel reserves could be deployed to the station provide an important measure of safety in the near term. As hydrogen technologies become more proven and experience in Antarctic grows, communities may rely on them exclusively for energy storage. However, until their performance is proven, having alternative solutions remains a wise approach to deploying hydrogen systems. System 2 also provides greater flexibility to adapt to changes at the station as new technologies are introduced or the roles of Antarctic stations change over time.

In summary, System 2 maximises the benefit of using hydrogen for energy storage without committing the operators to substantial capital costs, and the planned inclusion of fossil fuels compared to the other system designs provides a transition path for adoption, improved reliability, and greater flexibility in adapting to future energy demands or technology developments.

It is also important to note that the modelling process does not allow perfect representation of a wind-hydrogen(-diesel) energy system at Mawson Station. Calculations are made on an hourly basis regarding loads, mass and energy balances, and the operation of components. Functioning systems, however, operate on much shorter time steps (seconds or milliseconds). The models used for Mawson lack the capability to assess the combined heat and power generation capability of the station and a lower resolution calculation technique was applied to compensate for the lack of CHP functionality in the design. The data on user loads supplied by the station's operators, particularly thermal loads, was not a full and accurate representation of the contemporary situation, and required considerable processing for use in the simulations. The functionality of the models, under some circumstances, was shown to over-specify the minimum possible size of the fuel cell component by 15-30%.

All of these factors contribute to inaccuracy and variability in the modelling results. The configurations specified for each of the system designs should therefore be viewed as approximate designs. There is a risk that the systems may not perform the same in practice as indicated by the simulations which could compromise their overall operation. For example, Systems 1 and 3 specify and are critically dependent on large hydrogen systems to meet their operating goals. If the systems failed to perform as expected and did not have access to the same capacities of hydrogen storage or excess renewable energy, standby or emergency diesel fuel would be needed to meet an energy shortage. Such a failure would negate the value of the substantial investment in the hydrogen energy technologies. Poorer than expected performance from the hydrogen technologies in System 2, by comparison, could be easily addressed through minor changes to the diesel energy infrastructure included in the system design.

The inaccuracies embodied in the modelling process could also result in a conservative approach to specifying component sizes for the energy systems. Each of the systems specified may therefore be larger than realistically required by the station and presents a risk of over-investment in energy infrastructure.

Until solutions are developed to address the error contributions to the modelling process, it is wise to take a conservative approach to specifying system designs based strongly on the results of the modelling tool. System 2 remains the most preferred configuration as the potential impact of modelling errors on the viability of the system performance or the risk of over-investing in capital is minimised.

These issues highlight some final conclusions to be drawn from the modelling process. The collection of accurate and adequate data on renewable energy resources and energy demands is an essential component of any effort to evaluate potential energy system designs through computer modelling. The existing models used for Mawson require a number of corrections, particularly in relation to the propensity to specify over-sized fuel cell components. The accuracy of the results would also be greatly improved by the inclusion of components to represent the combined heat and power capability of the station's energy system. Future users of energy system tools such as those examined in this study should separate tasks between experts and non-expert (general) users as appropriate to optimise the use of labour and the capabilities of the modelling and analysis tools.

Further improvements to the models and the tools used for analysis and interpretation are also suggested for the following areas:
1. Enable the use of multiple components to replace single items in the models (e.g. 4x100 kW fuel cells for the 400kW capacity specified in System 1).
2. Create more flexible control systems that allow some of the multiple components to be turned off rather than idle (e.g. during known low load periods, set 2 fuel cells idling for quick response to load, and 2 turned off).
3. Develop predictive tools for energy system behaviour to increase the capability and 'intelligence' of control system. For example, identifying probable periods of excess wind energy from past experience of wind data and loads and contemporary circumstances would enable a control strategy to optimise the duty cycle of relevant components (e.g. turning on additional electrolysers to maximise hydrogen generation).
4. Automation of the model optimisation process.
5. Integrate analysis of life cycle and economic costs into the modelling and analysis process; either through calculation of the costs of results optimised on a technical basis or included as elements of the optimisation protocol.

8.6 *References*

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3. All users of the HYDROGEMS modelling library were registered by Ulleberg until late 2005, after which the library was formally supported by the TRNSYS software suppliers. The last records held by Ulleberg indicate ~150 users from 45 countries.
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6. Since mid-2004, a grid connected wind-hydrogen energy system has been providing the heating and electrical energy needs of a small community on the remote Norwegian island of Utsira. The system is designed to operate as grid-independent but can utilise the grid connection if required. The technology components include two Enercon 0.6 MW Wind turbines, grid stabilizing equipment, NHEL alkaline electrolyser, steel hydrogen storage tank (200 bar), and hydrogen electrification via converted diesel electric generator and fuel cell. The HYDROGEMS modelling toolbox was used extensively during the initial concept development and final design phases of the project. This system is one of (if not the) first of its kind in the world, and illustrated the value of the HYDROGEMS library as a design tool and contributed to the further development of the toolbox. The Utsira island project represented "best-practice" for the modelling of hydrogen-integrated stand-alone power systems, and the experiences gained in modelling the system are highly transferable to the Mawson system due to the similarities in component technologies, wind patterns and energy demands.
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10. Glöckner, R., *Hydrogen Stand-Alone Power System, a Technoeconomic Approach to Assessing the Market Potential of HSAPS.* Fuel cells for stationary applications—driving forward commercialisation and regulations, 2004.
11. HSAPS was a two-year, EU funded, project which sought to establish realistic market development projections for hydrogen and fuel cell technologies in small to medium sized remote power applications, completed

in 2004. The results from the project are readily transferable to the selection of components for the proposed Mawson hydrogen energy system, including forward projections of component costs, performance and availability in the medium-term (the year 2020). Report is accessible from http://www.ife.no/publications/2005/ensys/publication.2006-12-19.8849851129/fss_download/Attachmentfile

12. 1st law of thermodynamics: energy can be changed from one form to another, but it cannot be created or destroyed. 2nd law of thermodynamics (entropy): the energy available after a chemical reaction is less than that at the beginning of the reaction; energy conversions are not 100% efficient (energy is unavoidably converted into other undesired forms, e.g. heat).

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Chapter 9. Community perceptions of hydrogen energy

This research project has stated an objective of developing practical implementation strategies to enable the greater use of sustainable energy technologies in remote communities, focusing on the case study of Australia's operations in the Antarctic region and the introduction of hydrogen as an enabling technology.

The preceding chapters have provided an overview of the characteristics and operations of the Australian Antarctic research community and a detailed analysis of the potential roles of hydrogen technologies in the community. This information will provide a foundation for the development of implementation strategies that are specific to Antarctic communities and their uptake of hydrogen technologies.

However, as discussed in the literature review, community perceptions about new energy technologies such as hydrogen have proven to be critical in influencing the design, acceptance and introduction or uptake of the technologies. Numerous projects that have neglected to adequately understand the needs and attitudes of their target communities have suffered delays, been forced to undergo substantial (and expensive) changes, or ultimately have been terminated. Such results are neither effective nor sensible, and are far from an ideal result for the project developers or the communities.

Similarly, a failure to understand the needs and capabilities of a community significantly compromises the ability of a project developer to identify an energy system solution that is truly appropriate for the community. The major elements of a paper that presented a 'whole of system approach' and process for selecting appropriate energy solutions, developed by the author for the 2004 World Energy Congress [1], were presented in Chapter 5.

In contrast, if the needs of a target community and their knowledge and perceptions about key technologies are effectively understood, a project developer can ensure that a proposed energy solution is appropriate for the community, has been developed in consultation with the community, and has the informed support of the community decision makers (if not the whole community). The understanding can be further applied to ensure that the introduction and on-going operation of any new technologies is undertaken in a manner that also meets the community's needs and values.

Returning to the objective of this research, it is therefore critical that a comprehensive understanding of the knowledge and perceptions of the Australian Antarctic community towards hydrogen energy and related technologies be developed. The research activities presented in this chapter were undertaken as a first step in developing this understanding. The approach to the research is based on techniques commonly applied in the social sciences, in contrast to the technical and engineering focus of the previous research activities presented in this thesis. The results from this social science research will be combined with the information generated in the preceding chapters for the development of 'well rounded' implementation strategies and recommendations.

9.1 Research goals

The overall objective of this research component is to develop a comprehensive understanding of the knowledge and perceptions of the Australian Antarctic community towards hydrogen energy and related technologies. Four specific goals were subsequently defined to direct the research efforts – to:

1. Identify the current levels of knowledge about and perceptions of hydrogen energy technologies within the Australian Antarctic community, focusing on upper-level decision makers in the community.
2. Identify potential drivers for or barriers to the implementation of hydrogen technologies in the community, based on the hydrogen-related perceptions of the community members.
3. Determine if hydrogen energy technologies are appropriate solutions for the community, based on the values, culture and objectives of the community.
4. Capture knowledge and experience from other efforts around the world to implement hydrogen energy technologies to provide a broader perspective of the current drivers for and barriers to the use of hydrogen energy technologies in society – particularly their use in remote areas.

9.2 Research methods

Fulfilling these research goals required engagement with two key communities - the Australian Antarctic research community and the broader energy development community (focusing on community members involved with hydrogen energy). This engagement was used to develop an understanding of the key features of each of the communities and their activities, and to investigate the relationships between the two communities. A mixture of three formal and informal information collecting techniques was used. They include:

1. *Informal interviews and discussions* – A substantial number of informal interviews and discussions were held with key individuals over the three year period research. These meetings often had limited formal structure and were used to gain a broad understanding of contemporary issues and attitudes within the communities. Follow-up meetings enabled important changes and developments to be identified and evaluated. The meetings also helped to establish working relationships with a number of key stakeholders in the Antarctic and hydrogen communities. These relationships proved valuable in gaining more complete and open responses on potentially sensitive issues.
2. *Formal interviews and questionnaires* – Personal interviews were also conducted with selected individuals from the international Antarctic community (focusing on the Australian Antarctic community) or with individuals who had expertise relating to the implementation of hydrogen technologies. These interviews were formally structured and sanctioned by the University of Tasmania 'Human research project' ethical practices review process.
3. *Active community involvement* – Active and consistent participation in the Australian Antarctic community and the Australian energy community was an important component of the research method. The strategy enabled the development of an informal and 'grass roots' understanding of the communities. It also secured the interest and support of the communities and their subsequent participation in the more intrusive and formal components of the research program.

Further information on these techniques is presented below and the specific details of the methodologies and processes can be reviewed in Appendices 5 to 7.

9.2.1 Informal interviews and discussions

A broad understanding of the potential social impacts and challenges associated with the introduction of hydrogen technologies into the Australian Antarctic research community was primarily developed through an extensive series of informal meetings and discussions with individuals in the relevant communities.

Close relationships were subsequently established with 32 individuals within the Australian and international Antarctic research communities and the renewable and hydrogen energy development communities. Refer to Appendix 8 for a full list of these individuals. As detailed in the list, the fields of interest and levels of responsibility of the individuals were wide ranging. Participants include the co-chair of the International Partnership for the Hydrogen Economy (IPHE), sustainable energy policy development officers in the Australian government, a PhD student involved with the community acceptance of hydrogen bus trials, engineers responsible for Antarctic energy systems, leaders of Antarctic stations, and scientists using electrical devices to track seals in the southern ocean.

The relationships with these individuals were primarily facilitated through face-to-face meetings at the subjects' organisations or at conferences and seminars around the world. E-mail and telephone communications were used to maintain links and follow-up on discussions. Many other meetings and conversations were held with other individuals around the world, but were less significant in their direct contribution to the research.

The discussions were used to identify and explore elements of community characteristics, operations and attitudes that related to the use of energy and innovative energy technologies. The relationships were also used as sounding boards during the development of recommended strategies and actions to improve the access of the communities to more sustainable energy technologies.

Details of the discussions were recorded at the time in journal entries, and significant and recurring themes were also noted. Evaluation of the results from each meeting and their integration with the outcomes from other discussions often prompted follow-up discussions to explore issues further. The outcomes from the informal interviews also formed the basis for developing the specific question sets used in the formal interview component of the research.

9.2.2 Formal Interviews & Questionnaires

The network of community members that was established to informally collect information relating to hydrogen energy use in Antarctica provided a wealth of accurate and community-based knowledge. However, the process and methodology of the research was not structured in approach and did not fully capture the attitudes of the key decision makers within the relevant communities.

A formally structured research component was consequently developed to complement the informal information that had been collected and to specifically capture the attitudes of important community members towards key issues. This formal component utilised a series of set questions presented to 17 individuals within the Antarctic and hydrogen energy communities. Refer to Appendix 8 for a full list of these individuals. The interview candidates were selected to capture the views of specific positions or roles within the Australian Antarctic community (and other international elements), or to capture the knowledge of specific parties involved in other hydrogen energy implementation projects around the world. As detailed in the list in Appendix 8, several high ranking representatives from the Australian Antarctic community participated in the study, including the Director, Chief Scientist and Chief Engineer of the Australian Antarctic Division and the Tasmanian government minister responsible for Antarctic-related issues.

The interview candidates were categorized into three specific groups based upon their roles in the community and expertise with energy systems. The need for this separation was identified through analysis of the composition and decision-making structures of the Antarctic research community, and evaluation of the results from the informal discussions. The specific groups were defined, in relation to hydrogen energy implementation in Antarctic communities, as:

1. *Implementers* – people who were actively involved in the development and implementation of hydrogen energy technologies, or would be responsible for their implementation in a community.
2. *Implementation targets* - the potential users of hydrogen technologies in the international Antarctic community, effectively represented as the scientific research community.
3. *Implementation influencers* – individuals or parties who could influence the selection of energy supply systems for operations in Antarctica or other regions.

A specific set of interview questions were consequently prepared for each category of candidates to cater for the slightly different focus of the candidate's potential interaction with hydrogen technologies. The interview questions were developed after consideration of the hydrogen energy implementation-related issues that emerged from the preceding technical elements of this thesis and the informal discussions held with members of the Antarctic and hydrogen energy communities. The question sets contained between 10 and 14 individual questions. The questions were designed to capture the understanding or attitudes of the individuals on issues such as:

1. Understanding of contemporary and future roles of energy in their community,
2. Capabilities and issues associated with current energy supply solutions, potential roles and capabilities of innovative technologies such as hydrogen,
3. Potential issues associated with the implementation of hydrogen technologies,
4. Drivers and barriers to the use of hydrogen technologies in Antarctic communities.

The question sets also included reference questions to capture the candidates' current level of interaction and influence over energy systems and knowledge about hydrogen energy technologies.

As the research sought to capture the personal responses of specific candidates from a range of backgrounds to a series of common questions (within each category of participants), the questions were designed to elicit qualitative rather than quantitative responses. This approach was considered most appropriate for the types of candidates being interviewed, the forms of information that were sought and the range of responses anticipated.

The research methodology in this study included contacting potential interview candidates to invite their participation in the research, conducting personal interviews with the candidates using the structured question sets, and recording the verbal responses. The interview results were subsequently reviewed and transcribed by the researcher. When invited to participate, the interview candidates were informed that participation was wholly voluntary, their identity could be concealed, a personal interview of approximately 30 minutes duration was required, and the interview results were to be recorded. In addition to the 17 listed participants, 3 potential candidates declined to participate for legal reasons or other commitments, and 5 candidates did not respond to the invitation. None of the participants requested the suppression of their identity or objected to the recording of the interview; however, 3 candidates requested the recorder be turned off for additional 'off the record' responses during the interview. Two candidates completed the questions with written responses due to their remote locations. The formal interview research component was fully scrutinized and approved by the University of Tasmania Ethics Committee. Refer to Appendices 5, 6 and 7 for formal details of the interview methodology, as presented in the application for ethics approval.

Processing of the interview results was undertaken after each interview. Each interview generated considerable amounts of 'data' that needed to be recorded and then filtered to remove comments that were extraneous to the specific interview questions. The process involved review of the original interview results (recorded and/or transcribed) and distillation of the core components of the response to each question (by the researcher's assessment) to develop a summarized interview response. Significant quotes were also recorded where relevant. The full process of transcribing, evaluating and summarizing took several days for each candidate when their responses were concise and direct. A summary document of the interview responses was generated for each candidate, averaging approximately five pages in length. In some circumstances, the interviews extended to 1.5 hours in duration, with the candidates providing significant additional information beyond the specific set questions. This was seen as a positive outcome from the interview and engagement process, although processing of interview recordings took considerably longer than a few hours. For these interviews, the results were separated into 'summarised formal interview questions' and notes as from an informal discussion.

9.2.3 Community engagement

The activities presented above utilised formal or semi-formal interactions with individuals within the Antarctic and hydrogen energy communities to develop an understanding of the social issues associated with the implementation of hydrogen energy technologies into the Australian Antarctic research community. In addition to these actions, a significant amount of knowledge was also informally gained by becoming an active member of the Antarctic and hydrogen energy research communities.

The types of activities undertaken to facilitate engagement with these research communities included:

1. Basing the research project at Australia's only Antarctic-focused academic research institute, the Institute of Antarctic and Southern Ocean Studies (IASOS); and physically relocating to the geographic heart of the Australian Antarctic research community in Hobart, Tasmania. This provided constant exposure and interaction with a key element of the Antarctic community – the scientists and support personnel who work on the continent.

2. Securing part-time employment as a professional engineer with the Australian Antarctic Division (AAD), the leading government agency for Australian Antarctic affairs, including project work in Antarctica over the 2001-2 summer season. This provided a direct connection with the professionals responsible for the selection and operation of supporting infrastructure such as energy systems, and developed a practical appreciation of the challenges associated with delivering services to communities in Antarctica. The experience also provided valuable exposure to the members of the wider professional community that are involved in managing Australia's Antarctic interests, including bureaucrats, managers, recruiters, accountants, policy developers, and the personnel associated with the occupational health, safety and environmental characteristics of Antarctic operations.

3. Being an active participant in the broader activities of the Antarctic research community, including conferences, workshops, and public events. Also visiting the headquarters of the Norwegian, Swedish and British Antarctic research and support communities; informally attending the 2005 meeting of the international Antarctic community (Antarctic Treaty Consultative Meeting) in Sweden as a guest of the Swedish delegation; and presenting a poster at the 2006 meeting of the Standing Committee for Antarctic Logistics and Operations (SCALOP) committee as a guest of the Australian delegation [2].

4. Collaborating with researchers who focused on the technical aspects of hydrogen energy technologies, particularly colleagues at the University of Technology Sydney (UTS, Faculty of Engineering), the Norwegian Institute for Energy Technology (IFE, Energy Systems group); and the University of Tasmania (School of Engineering, Hydrogen and Allied Renewable Energy Technologies group).

5. Actively communicating with the key decision makers in relevant communities via workshops, briefings and seminars. The most significant events included a briefing to the Australian Greenhouse Office in 2003 that stimulated the provision of $500,000 to the AAD for a pilot wind-hydrogen energy system at Mawson station, and briefings to the Australian Bureau of Meteorology, Australian Antarctic Division, and Tasmanian Government's Office of Energy Planning and Conservation.

6. Involvement in broader activities in the Australian and international energy sector, particularly events that related to the development and implementation of hydrogen technologies. Actions included presentation of papers at a wide variety of conferences, participating in relevant workshops, and contributing to the development and management of professional networks through representation on committees. The most significant events in this category included participation in two World Hydrogen Energy Congress (WHEC) events (2002, 2004); contributing to

7. Employment through the University of Tasmania and independently as a consultant in the area of sustainable energy technology implementation, with clients including the Australian and Norwegian governments.

Further details on the full range of activities undertaken in order to actively engage with the Australian Antarctic and research communities are provided in Appendix 8.

Relevant outcomes from these unstructured 'engagement activities' were recorded in journal entries, and significant or recurring issues were highlighted. Issues that were identified or concepts that were developed as a consequence of involvement in broader community activities were often pursued through follow-up informal discussions with relevant individuals.

9.3 *Research results*

The three methods presented above yielded significant quantities of structured and unstructured information about the community-based issues that would influence the potential implementation of hydrogen energy technologies in Australia's Antarctic research community. Filtering and processing this large volume of data to generate useful and presentable results was quite a challenge.

The method selected to assess and present the results from the various information sources was to identify significant and recurring themes or issues that emerged after a three-tiered analysis process. These issues are represented through a series of 30 observations, from which specific conclusions are drawn in response to the specified goals for this research component.

The three tiers of the analysis process were:

1. The complete set of journal entries and summaries of interview results for all of the individual events undertaken as part of this research program were collated then reviewed as a specific and focused activity.
2. Significant themes and concepts that emerged from this review were identified for each of the three categories of data collection technique (namely informal discussions, formal interviews, and community engagement). As the different data collection techniques resulted in engagement with some common and some different individuals and collective groups within the Antarctic research and hydrogen energy communities, the results for each technique exhibited some commonality and also vast differences. The different time scales of the assessment techniques also resulted in different sets of observations.
3. The three sets of 'significant' results from the different data collection techniques were further reviewed to develop a single list of comprehensive observations that provided an effective representation of the many information sources captured during the research.

The 30 observations developed from this process are presented in the following pages. It must be emphasized that these observations represent hyper-summaries of the information gathered through this research.

A discussion of the combined significance of the observations and the research methodology is presented after the list of observations, followed by specific conclusions for this component of the thesis.

9.3.1 30 key observations from the community engagement process

Observation 1: in the early stages of this research program (circa 2002), the Australian Antarctic community (in general) had little interest in considering strategic energy issues and the evaluation of innovative energy technologies that could reduce their dependence on fossil fuels. That lack of interest made it very difficult to engage the community in regards to their perceptions and knowledge of hydrogen energy technologies. However, a small group of individuals were proactively working to raise awareness and the use of alternative energy technologies, and achieving this with increasing success.

Observation 2: the Australian Antarctic community is now (2007) far more engaged in the discussion and analysis of energy issues, and is receptive to the use of innovative energy technologies - including hydrogen.

Observation 3: Although a range of drivers can be identified for energy consuming communities, including those in Antarctica, to consider alternatives to fossil fuels for energy production, economic issues (ultimately the cost of energy) are the drivers most likely to attract attention and initiate a response from the community.

Observation 4: To external observers and some individuals within Antarctic communities, the perceived value of the 'untouched' nature of the Antarctic environment provides a compelling incentive for the communities to use clean energy technologies (compared to incentives in more conventional environments).

Observation 5: Within Antarctic communities, attitudes towards their compulsion or obligation to use significantly cleaner energy technologies are balanced by more pragmatic considerations than those of the external observers discussed in number 4.

Observation 6: Attitudes are changing within the Antarctic Treaty System towards the use of fossil fuels for energy production with greater consideration and acceptance of alternative energy technologies.

Observation 7: As a broad generalization, individuals within the Antarctic community (except those professionally involved with energy services) do not routinely consider the mechanisms, costs or environmental impacts of the energy systems they utilise to do their jobs. However, a growing number of such individuals are beginning to consider the broader issues associated with their use of energy and are more receptive to discussions about alternative energy supply systems.

Observation 8: Some members of the Antarctic community, particularly scientists undertaking field-based activities, have a growing need for energy solutions with operational capabilities that exceed those of conventional energy systems. These needs make them receptive to the introduction of innovative energy technologies if the technologies can offer enhanced performance. However, scientists also appear to have limited awareness of developments within the energy technology field that could deliver the performance enhancements that are needed.

Observation 9: Antarctic communities (particularly Australia's) have characteristics and cultures that would make it easier, relative to more conventional communities, to introduce innovative technologies such as hydrogen.

Observation 10: The largest barriers to accessing hydrogen technologies perceived by the Antarctic community include technology cost, proven performance, access to support infrastructure, and operational safety.

Observation 11: Although there are a wide range of energy-consuming activities undertaken in Antarctica, transport (shipping) rather than the operation of permanent and large-scale research stations is seen to have the highest impact on cost and environmental performance.

Observation 12: The majority of Antarctic communities operate relatively small-scale stationary power systems. These systems are comparable in size to a large number of remote area and village power systems around the world. In contrast, Australia's operations in Antarctica centre around three large facilities that have energy demands that are comparable in size to those of small rural towns.

Observation 13: Philosophical and operational changes in Australia's Antarctic research program that are being undertaken or considered indicate that small-scale and temporary field activities will become a more significant component of the program in the future. These actions will make Australia's need for small scale stationary energy systems more comparable to those of other operators in the region.

Observation 14: Inspiring visions of highly sustainable energy systems (e.g. 100% renewable energy) can be effectively used to gain initial attention and support in communities for the closer analysis of energy issues; however, these visions can also make the concepts and technologies appear too daunting and unachievable as they represent the highest cost and most technically-challenging solutions.

Observation 15: Energy system proposals that aim for more modest goals and can be better related to conventional systems are more likely to gain practical support for a range of practical and emotional reasons.

Observation 16: Antarctic communities (and perhaps energy-using communities in general) lack the resources and expertise to effectively understand and evaluate 'cutting edge' energy technologies such as hydrogen as their interests are focused on solutions currently available in the market place. The installation of wind turbines at Mawson Station, for example, was based on the modification of commercially-proven energy technologies for use in the Antarctic environment.

Observation 17: The challenges faced by the AAD with respect to energy systems are shared by other Antarctic operators, and are common to other remote communities – particularly those in similar physical environments such as the Arctic.

Observation 18: In parallel with Observation 1, in the early stages of this research program (circa 2002), there was very little awareness in the broad community, government or industry (particularly within Australia) of hydrogen energy technologies and the related issues.

Observation 19: In parallel with Observation 2, a greater awareness can be perceived within the broader community in regards to energy issues (environmental impacts, costs, security of supply) and energy users are more receptive to and knowledgeable about alternative energy technologies such as hydrogen.

Observation 20: Hydrogen technologies are in a rapid state of development and change, approaching pre-commercial status – they are generally more advanced than people outside the hydrogen field believe.

Observation 21: The concept of using hydrogen as a common energy carrier – a 'hydrogen economy' - has gained considerable political support on a global level in the past few years.

Observation 22: There is growing international interest in the development of sustainable energy systems for remote communities as an early market for hydrogen energy technologies.

Observation 23: Perceptions within the general Australian community towards hydrogen energy are mixed, and our engagement with the technology is limited in contrast to other developed nations.

Observation 24: Tasmania is emerging as a potentially strong player in the development and use of hydrogen technologies for remote communities through the collaborative efforts of the University of Tasmania and Hydro Tasmania (in addition to its existing strengths in supporting Antarctic operations and science) [4].

Observation 25: The greatest challenges facing the development of hydrogen energy systems are the cost of technologies and the need for the development of policies and standards to enable the manufacture and introduction of technologies into communities.

Observation 26: Practical and emotive aspects to the safety of hydrogen technologies are important in introducing hydrogen to communities.

Observation 27: There are a large number of issues beyond the development of hydrogen products that must be addressed before communities can effectively utilise the benefits of these technologies, and many should be initiated and managed by the communities.

Observation 28: Developing viable alternatives to fossil fuels for energy production, particularly the adoption of a hydrogen economy, is an immense undertaking, and is best achieved with collaboration and risk sharing.

Observation 29: Community responses to a proposal for the introduction of hydrogen technologies can vary considerably from very supportive and enthusiastic to highly negative and resistive.

Observation 30: When presented with the concept of using hydrogen energy at Antarctic stations, members of the energy development community are attracted to a variety of elements that they believe could assist in the broader development of hydrogen technologies (although these views are generally based on limited knowledge of Antarctic operations).

9.4 *Discussion: Response to the Research goals*

The discussion of the results from this component of the thesis will begin with an analysis of the results relative to the research goals, followed by an analysis of the methodology used in the research.

9.4.1 *Knowledge and perceptions of hydrogen technologies:*

Identifying the knowledge and perceptions of communities towards hydrogen energy technologies has been noted as an important component of the foundations to developing effective strategies to assist the communities in improving their access to more sustainable energy solutions. A strategy must ensure that the community has adequate levels of knowledge to make informed judgments about proposed solutions, and include actions to develop this knowledge and/or counter biased perceptions if necessary.

The first goal of this research action was to identify the 'base-line' level of knowledge within the Australian Antarctic community towards hydrogen energy. The information was subsequently used to develop specific strategies for the potential future implementation of hydrogen in Antarctic operations. The assessment of hydrogen perceptions has a specific 'time stamp' of mid 2005, the date at which the most critical perceptions were assessed and assembly of the implementation strategies began in earnest. This time reference is important as the knowledge and perceptions within and around the community with respect to hydrogen have changed significantly over the duration of this research and will continue to change in the future.

Details of the knowledge and perceptions of the Australian Antarctic research community were captured through interaction with the individuals and collective members of the community. The outcomes can be summarized as:

1. The key decision makers within the community are well informed with respect to the fundamental principles of the use of hydrogen as an energy storage mechanism and energy carrier. They are also aware of the growing maturity of hydrogen research, such as through the demonstration of hydrogen vehicles in the public arena. The Mawson Station "hydrogen demonstration project", as reviewed in Chapter 7, has also generated a more detailed understanding of the operation of a wind-hydrogen energy system.
2. The attitude of the key decision makers is much more difficult to quantify – responses in formal interviews are well balanced but non-committal, while informal responses (and anecdotal accounts) suggest that some personal perceptions may be more emotive and negative than indicated in the formal interviews. The formal responses of the key decision makers for the community could be summarized as: "the management of the AAD are supportive of novel energy technologies such as hydrogen if they can better assist the Division to fulfil its objectives, and meet minimum requirements for cost, performance and safety". However, off-the-record comments indicate that members of the AAD management perceive hydrogen technologies to still be very much in the realm of research and development and far from the levels of commercial maturity required for use in Antarctica. Consequently, it is seen as a deviation from the core interests and government-specified goals of the AAD to initiate involvement with such technologies at this time. It is not the role of this research to argue whether either of these views is more accurate, but the

difference between the 'on-record' and 'off-record' perceptions illustrates the challenges associated with developing an open discussion about the evaluation and possible introduction of new energy technologies for Antarctic operations.

3. The broader Antarctic community is reasonably well informed about hydrogen energy issues, but also appears to perceive the technologies as 'futuristic' and more appropriate to the realm of further research and development than application in Antarctic operations.

4. The majority of the broader Antarctic community is supportive of the principles of hydrogen energy use and the environmental, operational and security of supply advantages that can result. Negative perceptions emerge around the issue of funding the implementation of such technologies based on fears that funds for scientific research could be consumed. However, these perceptions relate more to the implementation of new energy systems than the specific technology being considered. Other negative responses emerged from the unlikely quarter of support personnel (diesel mechanics) fearing for their jobs in the near term; again, these perceptions cannot be attributed to the technology under consideration but rather a self-interested response to any action that may cause change to an existing system.

5. The safety of hydrogen energy technologies is a persistent factor in any discussions relating to their use in communities with attitudes ranging from misinformation-derived fear to pragmatic consideration of practical issues. The Australian Antarctic community appears to be aligned with the pragmatic response side of this spectrum – safety is an important issue in all aspects of Antarctic operations and appropriate and pragmatic questions were routinely asked about the relative safety and specific safety concerns of hydrogen technologies and their use in Antarctica.

During the course of the research program, attitudes within the Australian Antarctic community were seen to change markedly. Initial discussions with the community and efforts to secure funding within the AAD for hydrogen-related projects in 2001 and 2002 indicated that the community had negligible understanding of the use of hydrogen as an energy carrier or fuel. Although the fundamentals of the chemical reactions behind the concept could often be recalled from childhood education, the use of hydrogen as a practical energy storage mechanism was a novel concept for many people. Consequently, assessing the perceptions of the community towards the concept and associated technologies of a hydrogen energy economy for Antarctic communities was practically impossible. From an academic perspective, this level of knowledge and basic absence of viable perceptions could have served as the reference state for the development of hydrogen energy implementation strategies. However, two factors prompted a decision to attempt to increase the knowledge of the community about hydrogen energy issues as much as possible without influencing their perceptions.

The first of these influencing factors was an assessment that hydrogen technologies had reached a critical level of maturity and critical mass that would result in them entering the public arena over the course of the research. This entry was projected to expose the members of the Antarctic community to information about hydrogen energy that was available to the general public, thereby altering their knowledge and perceptions of the technology. This assessment was proven true, with a growing amount of material appearing each year in all forms of public media. Two important but unexpected actions also occurred that significantly influenced the knowledge of the Antarctic community towards hydrogen – the funding of a National Hydrogen Study by the Australian government [3] and the establishment of a hydrogen energy research centre at the University of Tasmania [4]. Taking a pro-active stance towards developing knowledge within the Antarctic community ensured that these two events provided positive contributions of information to a dynamic knowledge forum rather than disruptions to an idealistic and static assessment of the Antarctic community.

The second factor was an assessment that the very process of undertaking the different components of technical and non-technical research required for the thesis would raise the awareness and knowledge of the community.

As a consequence of these two factors, a wide range of actions were undertaken to provide the community and specific individuals with information about hydrogen energy technologies and their potential use in Antarctic operations. The goal in providing this information was to raise the knowledge of the community with respect to hydrogen energy technologies, with particularly regard to their use in Antarctic operations, without influencing the perceptions of the community towards the technology. The mechanisms were the many forms of community engagement undertaken as part of this research component and to promote a two-way exchange of information during any interactions with individuals.

Overall, the Australian Antarctic community does have an understanding of the fundamentals of the hydrogen economy concept but does not have a detailed understanding of the current state of development of hydrogen energy technologies; and is supportive of the potential use of the technologies if it is beneficial to their 'core business' of conducting scientific research, but believes that such use will occur in the future as further technology development is required. Some negative attitudes exist within the community but relate more to energy system change than to hydrogen technologies directly.

The process of engaging with the Antarctic community to improve their understanding of hydrogen technologies appeared to be of benefit to the community in comprehending general energy issues with more clarity, and having some knowledge of what solutions will be possible in the future. However, the active sharing of knowledge within the community could only be sustained for a short while during this research project. When presented with the subject of investing their own resources to maintain and improve the AAD's understanding and ability to evaluate hydrogen technologies, the pervasive attitude was that the technologies were not yet sufficiently advanced to warrant active monitoring of developments. This raised an obvious question in the mind of the author that "if the AAD does not get engaged with hydrogen because it is too immature, how can it tell when the technology has reached an appropriate level of development to justify their engagement?".

Previous efforts to the current research to actively assess developments in the hydrogen realm and their possible relevance to Antarctic operations had occurred almost a decade previously. It is the author's opinion, however, the current level of maturity of hydrogen technologies and rapid pace of further developments and commercialization suggests that waiting another decade before another detailed analysis would be a waste of valuable time. The time would be better spent developing knowledge of and experience with hydrogen technologies so as to fully appreciate the complexity of their operation. This would enable the AAD to effectively assess if and how such technologies can be integrated into their operations in the harsh polar environment. Significant acquisitions of hydrogen technologies may not occur for another decade as this knowledge and experience is developed, but during that period the technologies will become far more mature and cheaper and the AAD would be in a far better position to make informed decisions about the future direction of their energy services and the potential roles to be played by hydrogen energy technologies.

The second goal of this component of the thesis was to identify the potential drivers for and barriers to the implementation of hydrogen technologies in the Australian Antarctic community. These issues will be examined by first discussing the barriers, and then the drivers.

9.4.2 Barriers and challenges to hydrogen energy implementation

An early outcome from the research was that any efforts to facilitate the evaluation and implementation of more sustainable energy solutions for the Australian Antarctic community would have to address two primary tiers of challenges or barriers, and a range of more general and less significant "third-tier" issues.
The first and second-tier challenges include:
1. Those associated with establishing an open dialogue with and within the community about the energy supply solutions used by the community and the need to consider alternative options to existing systems; such dialogue would include recognition of the faults and issues associated with the conventional energy solutions, enable the fair consideration of alternative solutions and ensure that consensus can be established on the selection of appropriate solutions and implementation strategies.
2. Those associated with implementing novel technologies, such as hydrogen, into a community and managing the inevitable changes that are required in all areas of the community operations.

Considering the first tier of barriers, the AAD has not yet overcome these challenges. The following issues were identified as the major barriers that currently exist for the Australian Antarctic community:
1. A lack of appreciation of the full magnitude and extent of the potential threats that Antarctic energy systems are facing; the focus of the community to-date has justifiably been on Antarctic science, and trends in energy systems have been provided by market factors. There has previously been no need to undertake strategic analysis of energy issues. There is therefore limited support for examination of the ideas and issues.
2. A general acceptance within the Antarctic community of the environmental and economic performance of conventional energy systems; however, this attitude is changing due to growing external and internal pressure to improve environmental performance, demonstrations of the viability of alternative energy technologies, and the increasing cost of conventional fuel resources
3. A limited understanding of the full economic costs and operational capabilities and constraints of conventional energy systems, making it difficult to fairly evaluate alternative solutions.
4. A limited analysis of the future energy service needs of the community,

particularly in regards to change-driving initiatives such as the air transport system, making it difficult to assess the performance-based merits of conventional and alternative energy supply systems.

5. A perception that alternative technologies are not operationally or financially viable, reinforcing the view that conventional solutions are acceptable as they are the only viable solutions; however, this view is not accurate from a performance perspective and again does not take into account indicators of future economic conditions for energy systems.

6. The existence of an entrenched culture where 'research' into operational issues is not seen as 'core business' for a scientific research organisation and so receives little management support;

7. A limited capability to identify and appropriately evaluate potential solutions to the threats to future energy supply services due to historic practices of only utilising products and services that are freely available in the market and not engaging in operations-focused research activities. However, there are positive examples of how the capabilities and experience of the community is growing in this sector.

To consider these challenges in greater detail, the primary outcome from the analysis is the lack of recognition of the threats facing the community with respect to its current dependency on fossil fuels. This lack of recognition is resulting in a lack of action towards managing changes away from these fuels.

The unresponsive attitude of the community was first measured in 2002 at the commencement of research. The community exhibited little awareness of alternative energy technologies, showed no strong motivations for change, and possessed negligible resources or capabilities to evaluate the situation. This culture was attributed to the long-term operational and financial stability of the conventional energy systems. The consequences of this historic energy system stability are now emerging in the form of a lack of organizational awareness of and capability to undertake strategic analysis of energy services.

The barriers that must be addressed to overcome this issue include the focus and allocation of resources within the community on pure 'science', and the limited recognition by decision makers that the challenges facing the sustainability of the community's energy systems are unprecedented and cannot be addressed without additional resources.

From a positive perspective, change is occurring in the community's understanding of and response to the threats faced by conventional energy systems, with a noticeable change in attitudes within the community over the course of the research program. A range of causes for this change were discussed in the various observations, but the most significant driver has been the unplanned increases in the financial costs of the fuel energy systems. However, attitudes towards addressing these issues remain relatively short sighted – a submission in 2005 to the AAD executive committee (not by the author) about the likely impacts of fuel price rises consistent with recent trends of 20% p.a. for the next decade captured the attention of the decision makers and prompted action. Unfortunately, this action was effectively limited to making a submission to the Australian government for additional funding to cover future fuel price increases. There is also evidence of proactive efforts to evaluate alternative energy technologies – the wind turbines at Mawson are a high profile and high impact example of many smaller initiatives undertaken over the past two decades by individuals within the Operations and Science Branches. However, delicate exploration of the history of the Mawson wind turbine project and the more recent and relevant hydrogen demonstration project indicates that quasi-political issues were significant factors in securing support for the projects. Consequently the project are more representative of the success that can be achieved for one-off activities rather than serving as an indicator of proactive support for the wide-spread and unbiased evaluation of energy services throughout the organisation.

One of the greatest challenges to enabling the appropriate implementation of more sustainable energy solutions, therefore, is to raise awareness of the need for action, and for such action to be executed soon enough that the operations of the AAD are not disrupted by threats to their energy systems. The consequence of this existing lack of awareness, support and capacity for strategic analysis within the AAD is that appropriate and disruption-free changes may not be possible with the resources available in the future. To raise such awareness, it appears imperative that the point be highlighted to decision makers that novel and genuine threats to the future sustainability of Antarctic energy services are emerging in the realms of economic costs, environmental impacts, and operational performance. These are not alarmist predictions but sound advice based on rational assessment of current market and societal conditions and trends. The decision makers must be convinced that continued complete dependence on fossil fuels is not a viable strategy to ensure the sustainability of the energy services for Antarctic communities in the coming decades; changes to the foundations of conventional energy systems are required to ensure that their energy services will be cost effective, available, acceptable and suitable for the future needs of Antarctic scientists.

The communication of these issues is being achieved to some extent by members of the Operations branch, as illustrated by the support successfully gained for projects such as the wind turbines at Mawson. The community is also developing some capacity to assess these issues and develop solutions through the efforts of the Innovation & Development (I&D) Engineer; however, the magnitude of the challenges faced suggest that more substantial resources will be required to achieve genuine change and progress.

There is therefore a need to raise the awareness of the decision makers in the community with respect to the threats to their energy services in the future (particularly cost, environmental impacts and operational capabilities), and to promote the development of competency building. This research project has made some indirect efforts to address these issues, but identifying an appropriate champion for the cause in the future is a challenge. The Innovation & Development Engineer position at the AAD is the most likely candidate as the position is already resourced, and has a specified role of looking at future technology issues for the AAD. The current I&D engineer, Peter Magill, has already sustained a long-term campaign to raise the awareness of successive generations of AAD management about strategic energy issues and was subsequently successful with projects such as the wind turbines for Mawson. It is suggested, however, that the priority and profile of energy issues be increased in the future for the activities of the I&D Engineer.

The second major challenge is an attitude that the environmental performance of the conventional energy systems is adequate for the community's value system. This is a challenge for novel energy technologies such as hydrogen because much of their competitive advantage lies in their improved environmental performance relative to conventional solutions.

As the Antarctic community does not yet fully value the reductions in local and global environmental emissions that alternative energy systems can provide, solutions such as hydrogen will only be considered as appropriate substitutes for conventional systems if they can compete in other performance criteria considered important by the community. These criteria include the total cost of energy, performance capabilities and energy security.

It must be noted, however, that if the community does not seek energy supply solutions with improved environmental performance, then working to implement solutions based predominantly on these grounds is inappropriate (particularly if the solutions also fail to meet the needs of the community, such as lower economic cost).

At the present time, the prevalent attitude within the Antarctic Treaty System is an acceptance of the impacts of fossil fuels and a desire to mitigate those impacts as much as possible – but this mitigation does not extend to mandatory reductions in their use. These attitudes are neither universally held nor static; as noted in the observations, several indicators exist of a changing attitude towards fossil fuel use including bans under consideration for specific and highly sensitive regions of Antarctica. Based on these conditions, energy technologies such as renewables and hydrogen storage systems are appealing to the Antarctic community because of their environmental performance but will not receive specific support for these characteristics except in exceptional circumstances. If the trends emerging towards true minimization of environmental impacts in Antarctica continue then the acceptance of conventional solutions will be reduced and cleaner energy solutions may gain preference.

The third and fourth challenges are the limited levels of understanding within the community of these other important factors for assessing the performance of their energy supply solutions – the economic costs and performance constraints of the fossil fuel energy systems used to support operations in Antarctica for current and future activities.

A clear example of this challenge emerged during the business case development for the installation of the wind turbines at Mawson station: due to the complexity associated with calculating an accurate cost for diesel fuel delivered to the station in a ship that also conducted marine research and delivered cargo and personnel, the operating cost of the conventional diesel power system was calculated using the 'pump price' of diesel from Australia. This method ignored the costs associated with the transport and transfer of the fuel to the coastal Antarctic facility. Anecdotal views within the operations community of the Australian program indicate that the true cost of fuel 'at the station' is at least twice the pump price in Hobart, and costs can increase 5x to 10x for activities undertaken at in-land locations where further transport of smaller fuel volumes is required. This perverse bias towards the conventional energy system made the novel wind energy system appear even less economically attractive and further increased the challenges faced by the proponents in trying to secure support for the system. The business case for the turbines was ultimately approved with a payback period of approximately 15 years. As diesel costs have increased by approximately 40% since the development of the business case in 2001, the economic competitiveness of the system is improving even when transport costs (which have also increased significantly) are disregarded.

The genuine impact of transport requirements on Antarctic fuel costs becomes more significant when the strategic direction of the AAD is considered – the new air transport system will enable rapid deployment of personnel to more remote locations around the continent. This will have two clear impacts on energy costs with a greater proportion of shipping costs directly attributable to fuel delivery as people will be transported by aircraft (also making the full economic costs apparent) and increased volumes of fuel will need to be transported to non-coastal locations. The much smaller payload of the aircraft relative to ships will enable recording of flight movements necessary for fuel delivery, and the true cost of supplying fuel for energy systems to remote field camps will also become apparent.

The delivery to and use of fossil fuels in an increasing number of remote and temporary field locations also raises the issue of a potential increase of environmental impacts through storage, use and possible spillage of fuel. An alternative perspective to this negative view is that environmental impacts at inland locations are less likely to have a direct impact on wild life compared to the permanent and coastal stations. Consequently, the use of smaller field camps could be a positive step in reducing net environmental emissions even if fossil fuels are used. In either case, the tenets of the Antarctic Treaty System indicate that due consideration of the potential impacts from the presence of scientists and their energy systems in areas of interest must be made.

Other constraints for conventional energy systems, such as security of supply for fuels, are difficult to quantify but the likelihood of significant problems such as a failure to source fuel supplies is are increasing. Although the threats to supply are more likely to be in the form of having sufficient finances to buy the necessary volumes of fuel, there is a small but growing threat that fuel reserves may not be available. The 2005 hurricane seasons in the southern United States illustrated that extreme events can have significant impacts on the availability of fossil fuel reserves, driving up economic costs but also imposing physical limitations on availability.

A final constraint of conventional energy systems that is not well understood by the community is the increasing levels of energy supply performance required by a range of scientific technologies that are emerging. These technologies could improve the capability and value of Antarctic research but would struggle to be adequately supported by conventional energy systems.

At present, there is little collective understanding in the Antarctic community of these issues and the problems are not readily apparent - the energy and transport systems are interwoven and there has been little motivation to isolate costs; energy supplies have always been reliably available and conventional technologies have been able to meet the needs of scientists. To address this challenge, the community must develop an understanding of energy costs and the other factors to enable alterative solutions to accurately compete and to effectively plan for the significant changes to operations that will be possible via changes such as the air transport system or new scientific instruments.

The fifth major challenge is the apparent strong perception in the community that alternative energy technologies are not adequately competitive for use in Antarctic operations. When combined with the lack of support for strategic analysis of energy systems that was identified in the first challenge, this perception results in a negative feedback loop where attitudes towards the viability of novel technologies and the need for their use constrain the release of resources to accurately assess the merit of such technologies. A potential strategy to address this challenge would be to establish more and wider engagement with technology researchers and developers to identify the genuine capability and viability of alternative energy sources that have the potential for use in Antarctic operations. Such forms of engagement have begun through projects such as the Mawson wind turbines and hydrogen projects and other smaller renewable energy projects. However, as discussed above and in the observations, securing the necessary support for the larger projects were hard-won battles for the proponents. The projects are now progressing, but some senior decision makers still question the merits of the decisions and have only limited support for further efforts. Consequently, the engagement with external parties in relation to energy technologies is limited in scope and duration.

The sixth challenge is the strong culture within the AAD whereby the 'research' goals and activities of the organisation relate in practice only to pure scientific research tasks. Personal experience by the author in attempting to gain support through the research programs of the AAD for highly applied research relating to more sustainable energy services, and similar experiences by others, indicated that such activities were not seen as relevant by the scientific community. An interview with the Chief Scientist of the AAD to explore the issue established that energy-related scientific research would be 'fully eligible' for support through the AAD's programs, but such applications would be assessed (as with all applications for science support) against the stated science goals of the AAD and in competition with all other applications.

Whilst this represents an administrative 'green light' to apply for science support for energy-related research, the practical reality is that such activities cannot compete given the current research goals. As the competitive science support process controls access to resources such as berths on ships travelling to Antarctica and beds at the stations, and supporting resources such as infrastructure in Antarctica, even research activities that don't require cash funding (such as university-based PhD projects) cannot gain access to the Antarctic continent with the support of the science program.

The alternative approach, as applied by the author, is to gain access to the continent through the 'Operations Branch'. However, this requires participation in specific and practical projects that relate to the current operations of the stations and infrastructure, and have also been assessed as a priority relative to the other operational projects that are proposed each year and compete for funding and access to logistics and other resources. Research projects of any kind, including into energy services, cannot be supported in such a form by the Operations Branch (but could fortuitously be undertaken vicariously if the researcher happened to be in Antarctica for other operational reasons, as happened in the case of this research in 2003).

The seventh challenge is the limited capability of the Australian Antarctic community to identify, understand and respond to the potential future threats to energy services that have been identified and examined in this thesis. This limited capability is due to the past practice of generally using only products and services that are proven in common markets and so are cost effective, readily serviced, and of proven performance. This approach is logical due to the need for reliable equipment in Antarctica and the historic lack of need to evaluate new energy technologies when conventional technologies are highly suitable. Without a clear need to closely evaluate their energy services and possible alternative solutions, the AAD has not done so. There are, however, positive examples of how the capabilities and experience of the community is growing in this sector. The Mawson wind turbines, cited previously as an example of how the AAD has sought to access an innovative technology only when it is commercially mature, are also an example of how the AAD was able to critically evaluate their current and future energy needs and identify alternative solutions that were very different to current approaches. The successful commissioning of the turbines also demonstrates their ability to investigate and integrate new technologies into existing systems and to work with suppliers to ensure that the new technologies will perform well in the Antarctic environment (or can be modified to do so).

In addition to this collection of 'first-tier' challenges to the evaluation and implementation of more sustainable energy solutions, a series of second-tier and more general third-tier challenges were also identified. These challenges are specifically associated with the implementation of novel energy technologies such as hydrogen into a community, and become significant once the challenges in the first tier have been addressed. The second-tier challenges for the Australian Antarctic community in relation to the implementation of hydrogen and renewable energy systems include:

1. Existing financial structures for operations are not supportive of the different structures required for alternative energy technologies that are characterised by much higher capital costs but significantly reduced operating costs.
2. Gaining adequate expertise to effectively evaluate and select novel energy technologies for their specific integration into Antarctic operations.
3. Integrating novel technologies into existing infrastructure without adverse disruption to the physical and operating systems.
4. Accessing adequate support infrastructure for novel technologies.
5. Identifying and managing actual and perceived occupational health, safety and environment risks associated with operating novel equipment in the physical and operating environment characteristic of Antarctic research (air transport, harsh and freezing climate).

To consider these second-tier challenges in greater detail, the first challenge relates to the configuration of existing budgets and business models to include energy system infrastructure with moderate capital investments and moderate operating expenses. As alternative energy technologies such as wind turbines and hydrogen energy systems require large capital investments at the beginning of a project, accessing the necessary funds can be a challenge for operations with set annual budgets. As indicated with the Mawson wind turbine project, the development of a business case that includes the total infrastructure and operating costs of conventional and alternative energy systems can effectively illustrate the long-term competitiveness of alterative systems. Their competitive advantage lies in their reduced operating costs, and this advantage is set to improve as fossil fuel prices continue to rise. Although securing extra-ordinary funding for new energy infrastructure may be a challenge to the conventional budget processes of remote energy users such as the Antarctic community, increasing fuel prices are also creating unavoidable disruption of past budget allocation trends. Consequently, the changes to budget models that are being forced on remote power users by rising fuel costs could present opportunities for the development of alternative budget models that don't penalize the cost characteristics of alternative energy technologies.

The second of the 'tier-two' challenges to hydrogen implementation is associated with the limited expertise available within the Antarctic community to effectively evaluate and select alternative energy technologies. The lack of expertise alone is a barrier to the implementation of technologies such as hydrogen; however, the Antarctic community will also be challenged in developing the relationships necessary to overcome this barrier. The culture of 'no research in engineering' outlined in the first tier of implementation challenges will need to be resolved to enable the relevant members of the Antarctic community to develop the experiences and external relationships that will be required to evaluate, select and implement novel energy technologies. Potential actions that will be required include developing relationships with external energy technology researchers and suppliers to gain an understanding of products and systems, the purchase of components for evaluation and testing of their operation in Antarctica, and the construction of small-scale systems to enable 'learning by doing'. There is experience in the AAD with existing energy systems in dealing with some of these issues, but not a great deal of engagement with suppliers for most components. The wind turbines at Mawson Station are again an example of an exception to this observation, as their development required close engagement with the turbine manufacturers and the suppliers of the balance of plant for the energy system. The Hydrogen Demonstration Project is also enabling relationships with external parties who have become involved in minor section of the project (including technical colleges, the University of Tasmania, and commercial partners). Both projects, however, have dealt with specific products and tasks and not involved broader engagement with the research and development community of energy technologies and systems.

The integration of novel energy technologies such as hydrogen into existing operations and infrastructure was identified as the third set of second-tier challenges facing hydrogen energy implementation in Antarctic communities. New energy technologies will need to be integrated into the existing physical plant and equipment at the communities, and into the operational processes of the energy systems at the communities. Challenges will arise in areas such as maintaining operations as new technologies are installed, identifying and managing risks and maintaining service delivery during the transition phases, and maximizing the investment in existing infrastructure whilst introducing new systems at appropriate times.

The fourth set of challenges relates to securing adequate access to support infrastructure for new energy technologies such as for training of operators, maintenance and servicing of equipment, and responding to faults and problems.

The development of working relationships with external suppliers will be helpful in addressing these challenges.

The fifth set of challenges are derived from the need to identify, understand, and appropriately manage the occupational health, safety and environmental risks embodied in operating novel energy technologies, particularly in the harsh environment of Antarctica. As there is limited experience in the operation of hydrogen energy systems in real communities in a global context, Antarctic communities will need to identify and address generic risks associated with hydrogen technologies and the specific risks that may emerge due to their operation in the cold and remote Antarctic region.

Other more general challenges ("third-tier") associated with the implementation of hydrogen energy technologies into the Australian Antarctic community relate to:
1. The challenge of identifying the most appropriate point, in the development path of hydrogen energy technologies, for the community to begin actively engaging with the technologies.
2. The limited ability to make incremental changes to some areas of significant energy use in the community's operations (e.g. shipping).

The first of these third-tier challenges – the question of timing – relates to balancing the consequences of delaying the point in time that a community actively engages with a new and beneficial energy technology against the costs of engaging with the technology too soon. For the Australian Antarctic community, engaging with hydrogen too early could result in a system that is overly demanding of resources and therefore restricts the broader operations of the community. Conversely, engaging with the technologies after too long a delay could reduce the eventual capability of the community to respond to the need for changes in their energy system due to the growing financial burden of the conventional system. In either case, a poorly-timed response will compromise the capabilities of the community and their goals to undertake scientific research as excessive amounts of resources will be dedicated to the energy systems that are needed to support the science programs. An appropriate solution is to take a scientific approach to the problem by taking the steps necessary to enable a properly-informed decision about the threats facing the community and the appropriate time and extent to respond; this could be achieved by initiating some degree of small-scale engagement with the technologies in a concerted and strategic manner. The information gained could be used to develop a strategy for engagement with the technologies in the long term. The Mawson Hydrogen Demonstration Project is now contributing information in this manner, and was proposed by the author based on this concept.

The second of these third-tier challenges is the constrained ability of the Antarctic community to apply the approach suggested in the paragraph above to some elements of their operations that consume significant amounts of energy. An obvious example of this situation is the use of fossil fuels in the shipping and air transport systems that form the backbone of Antarctic logistics and passenger transport. The AAD's three permanent Antarctic stations, for example, each consumed roughly 600,000 litres of fuel in 2001. In contrast, the AAD's shipping program consumed approximately 3.6 million litres of SAB diesel fuel in the same year – six times more fuel (and associated carbon dioxide emissions) than each station (more specific figures are presented in Table 4.2 in section 4.5.2). This thesis has focused on the possibilities of using hydrogen and renewable energy technologies to reduce the use of fossil fuels at the large stations (particularly Mawson) due to the natural suitability of the technologies for such applications. Unfortunately for the AAD, the wide range and scope of alternative methods for meeting the energy needs of stations using technologies such as hydrogen are not available for the shipping and air transport programs. It is also far less likely that novel energy technologies could be introduced into transport systems in the multi-stage manner proposed for situations such as Mawson station. The AAD is therefore highly constrained in its ability to address the environmental and economic impacts of their use of large amounts of fossil fuels in their shipping and air transport systems.

To summarise the outcome from this multi-tiered analysis of the challenges facing hydrogen energy use in the Australian Antarctic community, the AAD is not widely experienced with having to consider potential problems with their energy systems and undertaking significant changes, and so has little awareness of the looming challenges they will face, let alone the capability to understand and evaluate their options and to implement changes. With fossil fuels providing relatively cheap, reliable and adequate energy services, there has been no motivation for change. The organisation has also grown around these systems so that station designs, operational strategies and funding mechanisms have all assumed the availability of the energy resource without disruption. The organisation, therefore, has no formal framework for dialogue on or conducting action about such problems.

This characteristic results in little support for the evaluation of alternative energy technologies and the discussion of strategic energy issues. The lack of framework also means that there is no clearly discernible strategy or policy relating to energy services within the AAD, beyond that of utilising common and conventional energy supply systems. There is, therefore, a need to raise awareness of these issues and secure support for change in the AAD's approach to understanding and addressing its current and future energy services. Outcomes from this research suggest that the key decision makers within the AAD are becoming aware of the issues and have some strategies in mind to address the challenges that they perceive as significant. A lengthy discussion with the AAD Director confirmed that a strategy does exist in relation to energy services for the AAD, including an imperative to reduce operating costs of stations by 50% within a decade. Management also view other significant drivers for change such as the air transport project as an opportunity to drive change in the energy arena – but pragmatic considerations, particularly cost, must be addressed. This strategy, however, does not exist in any written format and so is difficult to communicate to others, evaluate, and measure performance against.

9.4.3 Drivers and opportunities for hydrogen energy implementation

Through the community consultation process, the following 12 opportunities and drivers for the Australian Antarctic community to evaluate and implement hydrogen energy technologies were identified (or confirmed in many cases):

1. Environmental protection; the legal mandate and moral obligation to preserve and protect the Antarctic environment is a strong driver to consider cleaner energy systems, particularly solutions that are not dependent on polluting fossil fuels. For the Australian Antarctic community, which regards its high standing in the

international Antarctic community with respect to environmental issues as an important political tool, there may also be political merit and therefore drivers in implementing innovative sustainable energy technologies such as hydrogen. The widespread communication of the installation of the wind turbines at Mawson station and associated environmental benefits, for example, illustrates that the AAD perceives value in such activities.

The environmental protection issue was initially perceived by the author as potentially the strongest driver for changes in Antarctic energy systems. However, upon analysis it is not as strong as expected due to the pragmatic approach of both the Australian and international communities about the use of fossil fuels in Antarctica, and to a lesser extent, the lack of knowledge within the broader community about energy supply solutions in Antarctica and the associated risks of fossil fuel spills.

As mentioned in Chapter 4, the return to Australia of the third wind turbine from Mawson Station for sale, when the entire energy system was configured for its installation, is a compelling indicator of the conflicting degrees of support for the project within the AAD management and of the limited influence that the environment has as a driver for deploying cleaner energy technologies in Antarctic operations. With hindsight, it appears to the author that the turbine project was most likely undertaken for quasi-political reasons and is more of a one-off activity than a genuine indicator of proactive support for the wide-spread and unbiased evaluation of sustainable energy services in the organisation.

Although environmental issues are not as significant an issue as expected for the Australian Antarctic community, they have become more significant over the course of this study. This increase in significance correlates with changes in the awareness and frequency of actions relating to environmental issues in the broader community. External events such as the signing of the Kyoto protocol indicate that dialogue about environmental impacts is being turned into some form of action (although Australia continues to abstain from this instrument). This general awareness and activity is translating into the international Antarctic arena in the form of specific actions for organisations (for example, the AAD gaining ISO certification for environmental practices). However, as indicated by discussions with senior personnel within the Australian and international Antarctic communities, there is no clear consensus that the use of fossil fuels in Antarctica should be actively discouraged due to environmental reasons. Therefore, environmental issues continue to have limited influence as drivers for Antarctic communities to introduce alternative energy technologies such as hydrogen.

2. Economic costs; Antarctic communities pay some of the highest prices in the world for their energy services even though they use conventional and readily available energy technologies. As detailed in Chapter 4, the exact cost of energy services in Antarctica is difficult to determine, but prices have been proposed to be as high as five to ten times the 'pump price' of bulk fuel purchases in the developed world (i.e. such as from the Antarctic gateway city of Hobart in Australia). The high cost of energy is directly associated with the physical isolation of the Antarctic continent from the rest of the world and the subsequent transport costs associated with delivering fossil fuels to the Antarctic coast and activities around the continent.

The high cost of conventional energy systems is a strong motivator to identify methods of reducing the usage of fossil fuels, including the installation of alternative sources of primary energy like renewable energy technologies. High conventional energy costs also provide an opportunity for novel energy technologies like renewables, which are generally more expensive than conventional energy technologies when used in conventional circumstances, to compete more effectively on an economic basis in Antarctic operations. During the course of this research, Antarctic energy supply costs have also been impacted by the substantial increase in the market price of fossil fuels. Discussions with AAD engineering personnel indicate that price of diesel fuel used by the Antarctic community has increased by approximately twenty percent per year during this study. These increases in cost for the already expensive energy systems used by the Australian Antarctic community are the most compelling drivers for change within the Antarctic program.

3. Operational performance; the inadequacy of conventional energy technologies to meet a growing range of energy demands in Antarctic operations, particularly in the support of science programs, provides a strong driver for the use of renewable energy technologies.

4. Other activities that will result in significant changes in the Antarctic community's operations, such as the development of an intercontinental air transport link and changes to the strategic plan for science research, provide opportunities and drivers for the introduction of changes in energy systems.

5. The commonality of energy supply issues in Antarctic operations with other energy users around the world, particularly those in remote environments, provides opportunities for Antarctic energy users to access more sustainable energy solutions that are developed for applications around the world.

6. The quickly changing awareness within the general community towards energy and environmental issues may provide broader support to pursue cleaner energy options in Antarctica, even if these come at a higher economic cost. The Antarctic community could use this awareness to secure support within the government for any additional funds needed to introduce more sustainable energy systems.

7. The rapid rate of development of hydrogen energy technologies suggests that commercially mature products will be available soon. The interest of developers and researchers in using remote communities as early markets for such products suggests that some of their first products will be targeted at such applications – an obvious opportunity for Antarctic communities to access hydrogen technologies designed for their kind of operations.

8. A growing political and governmental interest in and support for non-fossil energy systems in general, and specifically for the concept of a hydrogen energy economy, is providing opportunities for Antarctic communities to implement hydrogen energy technologies. Governments are becoming better informed about hydrogen technologies and more supportive of activities aimed at developing competence and driving technology uptake.

9. The development of hydrogen technology skills and knowledge in Tasmania, such

as through the University of Tasmania [4], is providing the Australian Antarctic community with localised access to relevant and specialized skills. This access can address some of the key barriers to evaluating hydrogen technologies, namely the availability of appropriate support infrastructure.

10. The generally high level of education for personnel within the Australian Antarctic community and a well-developed culture of safety both provide opportunities for the community to evaluate hydrogen technologies in comparison to more conventional remote communities.

11. The strong communication links and long history of collaboration and sharing of knowledge between the members of the international Antarctic community will provide opportunities for specific communities (such as the Australians) to access the expertise of other communities who may be making similar efforts to develop more sustainable energy solutions. The networks within the international community could also be used to establish common needs for sustainable energy solutions and the presentation of these unified needs to technology suppliers. The packaging of larger orders could provide opportunities to negotiate lower individual component costs or more simply to attract the serious attention of technology developers who are looking for viable early markets for their products. The creation of a unified network of purchasers for novel energy technologies such as hydrogen would also create opportunities for Antarctic communities to engage with technology developers for the possible modification of conventional products, a level of commitment that the developers may be reluctant to make for smaller product orders.

12. The attraction that energy researchers and developers have for the concept of using Antarctic communities as isolated and high-profile early markets for hydrogen technologies creates obvious opportunities for Antarctic communities to exploit this interest to have more sustainable energy systems developed and implemented in Antarctic operations.

9.4.4 Evaluating if hydrogen technologies are appropriate for Antarctic operations?

The previous chapters reviewed the Australian Antarctic community's operations in Antarctica and indicate that there are two types of primary energy used in Antarctica – the largest component being imported and polluting fossil fuels, followed by a relatively small but growing use of renewable energy (wind and solar power). These fuels provide the energy required by the diverse range of operations that represent the integrated 'Antarctic energy system', and include stationary, transport-related and mobile energy consuming activities.

The extensive use of fossil fuels enables the Antarctic energy system to adequately meet the needs of the community (e.g. energy systems that are cost effective, reliable, maintainable, understandable, flexible, etc.), but does conflict (in principle) with the community value of protecting the pristine environment. Historically, this practice has been appropriate as there were very few (or no) viable options to provide energy in Antarctica without the use of imported and polluting fossil fuels, forcing a compromise between the practical need for energy to enable operations in Antarctica and the dependence on resources that impact the environment.

Although the community has accepted that the impact of fossil fuels is unavoidable to some degree, they have sought (and succeeded) to mitigate their impacts via techniques such as pursuing energy efficiency, upgrading technology components, and educating users. These methods are the cheapest and best methods to reduce and better manage energy consumption and subsequently reduce fossil fuel use, and are sensible and appropriate solutions for the energy system and the needs of the community.

The community is also pursuing greater use of renewable energy – a primary energy resource that offers substantially cleaner energy generation but reduces the flexibility and reliability of the system. The Mawson station design is an example of a highly-evolved system that uses renewable energy resources where possible and uses conventional energy technologies to provide the necessary back-up and balance of capacity. This system is being trialled for the intended expansion of renewable energy use at the other stations. In comparison to conventional systems that utilise only fossil fuels, the wind-diesel hybrid system at Mawson is even more appropriate and a logical next step for the other stations. However, evaluating the performance of the system at a single station is also an appropriate first action for the improvement of the total energy system managed by the Antarctic community.

The Antarctic community's evaluation of the technical viability of using hydrogen as an energy carrier for excess wind energy is also an appropriate action for improving the overall performance of Antarctic energy systems. In the Mawson evaluation, hydrogen could provide a means to replace the balance of diesel fuel used at the station and the fuels required for vehicles. The techniques and experiences developed at Mawson could then be transferred to the other stations in time. Ultimately, the development of an energy system free of fossil fuels that meets the strict operating requirements (reliable, robust, flexible etc) will be the most appropriate energy solution for Antarctic operations. As hydrogen technologies can make such systems possible, their use in Antarctic operations is theoretically appropriate. However, as with the gradual testing and implementation of renewable energy resources into Antarctic operations, a visionary yet cautious and pragmatic approach to utilising innovative energy solutions is the most appropriate method of progress towards fossil fuel-free operations.

From a broader perspective, the evaluation of wind-hydrogen technologies at Mawson station is also an appropriate action for the Antarctic community due to the potential for the system to serve as a high-profile demonstration of the capability of renewable energy technologies to provide sustainable energy systems for remote communities. The hydrogen project is funded by the Australian government's Greenhouse Office [5] in recognition of this potential to serve as a 'lighthouse' to other energy system developers and user communities [6].

9.4.5 Linking experiences with hydrogen in Antarctica to other projects and places

This research thesis began with a comprehensive analysis of the significance and methods of supplying energy in the modern world. A range of issues emerged from the literature review that were shown to be shared by energy using communities around the world – linking Antarctic research facilities, contemporary cities, and communities in the developing world. The concept was also presented that actions to implement hydrogen energy technologies in Australia's Antarctic communities could be of relevance to other communities and applications. This component of the research thesis has identified several mechanisms by which the evaluation, implementation and use of hydrogen technologies by Antarctic communities can influence other energy users, including:

1. The use of hydrogen systems in Antarctic operations can provide an effective demonstration of the hydrogen economy concept and the technical possibility of using hydrogen as a means of storing renewable energy resources for stationary and mobile applications, particularly in remote regions. Such demonstrations could serve as an inspiration to other communities to pursue their own solutions, whether they be similar in configuration to the systems used in Antarctic or simply based on the same concept of hydrogen as an energy carrier.

2. The individual technologies and integrated system solutions that have proven performance in Antarctica operations can be transferred, either as general examples of renewable-hydrogen energy systems or as designs for specific systems suitable for use in very cold and harsh environments.

3. The techniques to evaluate the use and implementation of innovative technologies (particularly hydrogen) into specific user communities and applications can be transferred to other applications.

4. Similarly, the methods of selecting components and designing systems can be transferred to other communities, including any enabling policies and standards.

5. The methods and experiences of implementing hydrogen technologies into operations and those derived from on-going usage and maintenance of the technologies can also be transferred to other applications.

6. Hydrogen use in Australia's Antarctic program could stimulate a growing market for hydrogen energy technologies in other Antarctic communities, thereby stimulating the further development of hydrogen technologies and consequential expansions in product variety and capability and reductions in cost. This could ultimately make hydrogen energy technologies more accessible to energy users for other applications.

7. Hydrogen use in Antarctica would also stimulate the development of supporting infrastructure for the related technologies and energy systems, including expertise in system design and evaluation, maintenance, and servicing that can be utilised by other users of hydrogen technologies.

8. The use of hydrogen in Antarctica could serve as a test bed for the hydrogen economy concept on a larger scale through the optimization of energy system designs and implementation techniques within a small and closed community. This would also allow practice of the precautionary principle for evaluation of the possible negative consequences of hydrogen energy use [7] before expansion of the systems to larger global markets.

The knowledge and experiences of Antarctic communities with hydrogen energy technologies can be transferred to other energy users on the basis of related organisational or community characteristics and cultures, physical environments (remote or polar regions, weather conditions etc.), activities and associated energy needs, the capabilities and resources and resources of the communities, and/or the design of existing energy systems for the communities. The knowledge and experiences of Antarctic communities can also be of relevance to technology developers and energy system researchers.

The degree to which the experiences of Antarctic communities with hydrogen energy technologies can be transferred to other communities, particularly the direct transfer of technologies and implementation strategies, is dependent on the level of similarities in these categories between the two communities.

Based on these definitions, several specific types of alterative energy-using applications and communities can be identified as likely candidates for the direct transfer of technologies or experiences developed from the use of hydrogen energy technologies in the Australian Antarctic community.
They include:
1. Other national Antarctic research programs,
2. Non-government Antarctic operators (tourism etc),
3. Research communities in the Arctic region,
4. Conventional communities in polar regions in the northern and southern hemispheres (Arctic and sub-Antarctic environments),
5. Niche applications that have strong drivers to utilise energy technologies that offer more secure or environmentally friendly energy solutions (e.g. military, eco-tourism, science, telecommunications industries),
6. Conventional communities in remote regions around the world (e.g. the Australian outback or equatorial islands),
7. Under-developed communities without access to conventional energy services.

Over the course of this research project, a number of comparable projects have been undertaken that relate to the case study considered for Mawson station in this research, demonstrating the high degree of relevance that can exist between hydrogen-related projects in Antarctica and other projects around the world. The projects include:

1. *Hydrogen for Stand Alone Power Systems (HSAPS) project* – the two-year desktop study undertook a range of project analyses and costings for remote communities in EU to adopt hydrogen energy technologies; the 2004 report presented real costs for components and projected cost reductions in the future, levels of technical viability, and suggested that Arctic communities are potentially viable markets as early adopters of hydrogen technologies due to their high cost of energy from conventional systems [8].

2. *Prince Edward Island (PEI) Wind-Hydrogen Village Project* – Canada's first wind-hydrogen village demonstration. Over a three year period beginning in 2006, the multifaceted initiative "will demonstrate, in real-life and in real-time, how wind energy and hydrogen technologies can work together to offer clean and sustainable energy solutions across a wide range of applications" [9, 10]. The applications will

include the installation of a hydrogen energy station, a hydrogen storage depot, and a wind-hydrogen and wind-diesel integrated control system to power a number of homes and buildings in the North Cape area. Subsequent phases are expected to include a hydrogen refuelling station to support the refuelling needs of up to three full-service hydrogen shuttle buses, the deployment of fuel cell utility vehicles, and the expansion of the wind-hydrogen village to provide energy for additional buildings and facilities, including at least one farm operation. The final phase of the project is expected to involve the introduction of a hydrogen-powered tour boat.

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3. *Iceland's National Hydrogen Energy Economy* - In 1998, Iceland declared its intention to eliminate its dependence on fossil fuels in favour of a national energy economy that used hydrogen as an energy carrier for renewable energy resources. The Icelandic New Energy (INE) company was formed to manage a transition plan with five phases that would enable the energy transformation to be completed by 2030 or 2040 [11, 12]. With these ambitious goals, Iceland has attracted a lot of interest and favourable media coverage and inspired energy researchers other projects around the world. However, as reviewed in a recent WorldWatch Institute article, the project is not progressing as dynamically as expected; "Officially, the national hydrogen agenda is unchanged, and Iceland continues to receive tremendous favourable media attention for its hydrogen plans. But the only material evidence of the transition is three hydrogen-powered buses that have roamed the streets of Reykjavík since 2003, fuelled by a single electrolyser station. No fleet expansion seems imminent, despite promises, nor are there any hydrogen ships or cars. More importantly, no research facilities have been built and no hydrogen industry is materializing. In fact, Iceland's hydrogen production is actually declining" [13]. INE argues that many research and promotional projects are also on the agenda, and the projects listed must be considered as the first phase in a series of projects. The next phases will be to introduce private vehicles using hydrogen, and a test with boats at first using fuel cells for their auxiliary equipment and later for their main propulsion [14].

4. *PURE (Promoting Unst Renewable Energy) project* (Shetland Islands) – a "pioneering project on the windswept island of Unst, the most northerly island in the British Isles". It demonstrates how wind power and hydrogen technology can be combined to provide the energy needs for a remote rural industrial estate. It was commissioned by the Unst Partnership Ltd., a community development agency established by the Unst Community Council to support local economic development and regeneration. It is cited as the first community-owned renewable energy project of its kind in the world. Significant differences between the PURE project and other hydrogen energy systems deployed around the world are cited to include the scale and the low budget (approximately £350,000) within which it was developed. The budget included all the engineering and consultancy works surrounding the project and the hardware [15].

5. *International Polar Year (IPY) 2007-2008 projects* – the IPY is anticipated to be an intense, internationally-coordinated campaign of research that will initiate a new era in polar science and will include research in both polar regions and recognise the strong links these regions have with the rest of the globe. It will involve a wide range of research disciplines, including the social sciences, but the emphasis will be interdisciplinary in its approach and truly international in participation. It aims to

educate and involve the public, and to help train the next generation of engineers, scientists, and leaders [16]. The broad approach of the IPY objectives and the collaborative approach have resulted in a wide range of project proposals from research groups around the world. In addition to the general relevance of the IPY to this research project through its goals to link polar regions together and with the rest of the world, a review of the proposed projects confirms that sustainable energy issues, including hydrogen energy, are being considered under the scope of the IPY [17].

6. *Utsira Island project* – a demonstration project, proposed in 2003 and commissioned in 2005, aimed to show how wind power and hydrogen can provide all the energy needed in a community to make it fully independent of fossil fuels. It is cited as the first full scale project of its kind in the world and as a "barrier-breaking milestone in the development of green energy systems". The developers, Norske Hydro did and do not expect it to be commercially viable, but view the project as still having great value as it will give them the unique experience of building and operating a future-oriented plant [18, 19].

7. *West Nordic project* – Together with local actors from the Faeroe Islands, Greenland and Iceland, Nordic Energy Research organisation studied different alternatives for distributed energy production systems for scarcely populated areas (2004-2006). The work consisted of mapping the present energy situation, the development of modelling tools for efficient and flexible analyses, and application of these tools in simulations to find suitable technical concepts and locations for possible future demonstration plants based on environmentally friendly energy production solutions. The results showed that solutions could be based on hydrogen technology combined with wind power (especially the Faeroe Islands) and solar power or small scale hydro power (especially Greenland) [20]. The research also concluded that there is a need for communities to develop highly efficient energy systems (particularly heating) before considering high value improvements such as hydrogen technologies; that hydrogen systems would be technically viable but diesel costs at present are too low for hydrogen technologies to compete on an economic basis due to subsidies for transport costs; and there is a need to consider issues associated with operation in the long-term such as starting the training of plant operators in technical colleges. Detailed simulations of conventional and renewable technology based energy systems with price fuel and component costs were also undertaken and offer an improved understanding of the potential to use renewable energy resources to insulate communities against the economic uncertainties and inevitable prices rises associated with the use of diesel fuel for energy generation [21].

All of these projects demonstrate the similarities in interest and approach towards the use of hydrogen technologies with renewable energy resources in remote communities around the world, particularly in cold and harsh environments. With the exception of the Icelandic example, all of the projects were also conceived and initiated after the commencement of this research project. The simultaneous execution of the different projects provided opportunities for active and passive linking of activities amongst the projects, including with this study.

The Icelandic project, for example, served as a powerful inspiration for commencing the research and as a demonstration of the respect that the hydrogen economy concept had secured from energy professionals around the world. The HSAPS project provided relevant data on the current and future viability of hydrogen energy technologies. Specifications captured through the analysis were also used in the Mawson station energy system modelling component of this research. The computer modelling work undertaken in the West Nordic and Utsira Island projects utilised the same custom-developed modelling package

Of the seven projects, however, the final two deserve particular mention due to their strong relevance to this research project in terms of the practical roles of hydrogen and renewable energy technologies and the importance and influence of economic factors as drivers for remote communities to pursue more sustainable energy technologies.

The Utsira island project has demonstrated that it is technically possible to use wind-hydrogen energy systems in remote communities. Having such a practical example was a very useful tool in discussions and interviews with the Antarctic community. The fact that the project used the same wind turbine manufacturer as the turbines at Mawson station further strengthened the argument. The Utsira system design, when it was finally commissioned, also validated some of the theoretical proposals and specific results derived from the computer modelling in this research – specifically the value in the use of fuel cells (FC) and hydrogen converted diesel electric generators (HEGS) in energy systems. The Utsira system development also had a very direct impact on the progress of this research. The experiences, skills and knowledge developed by the Institute for Energy Technology (IFE) in Norway with the energy system modelling package used to design the Utsira system were subsequently used to engineer a generic wind-hydrogen energy system modelling toolbox (Hydrogems) [22]. The toolbox was then made available to the author for the modelling of wind-hydrogen energy system designs for Mawson Station.

The West Nordic project applied the same energy system analysis software as that used for Utsira Island and in this research. It is the results of the economic analysis of introducing renewable energy technologies into remote communities that is most compelling, particularly in relation to the results of this Chapter where the economic costs of energy services in Antarctic operations were determined to be the strongest drivers for change.

The principal concepts from the West Nordic project results are presented in Figure 9.1, which compares the total cost of energy for a community relative to increases in the price of diesel fuel for four energy systems with differing levels of renewable energy penetration. As the original data was developed from communities living in remote areas, the 'cost of fuel' values include the expenses associated with delivery. The project final report includes graphs with specific data about specific communities. The general trends of these graphs, however, are highly relevant and transferable to the use of renewable energy technologies by other communities in remote areas around the world.

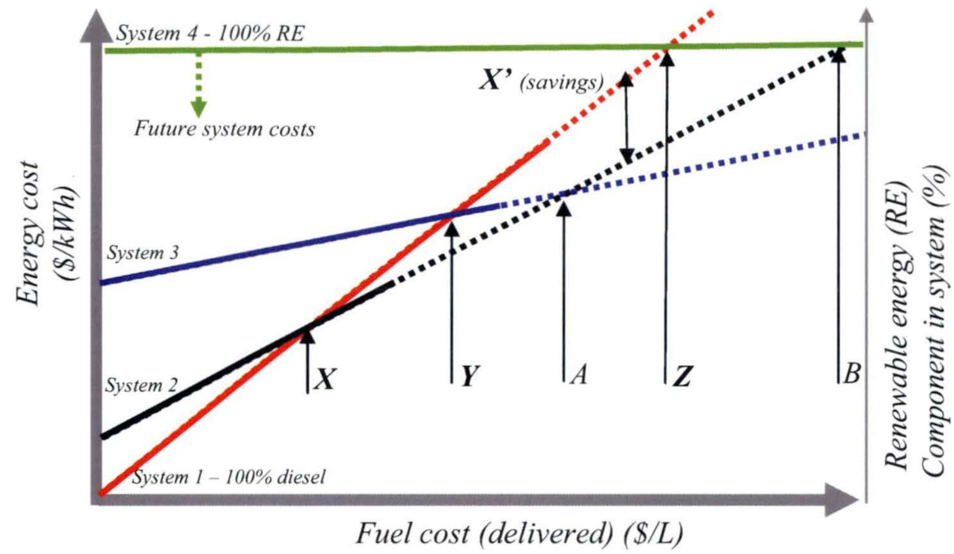

Figure 9.1: influence of renewable energy use in energy systems on the cost of energy.

The graph illustrates how the cost of energy for systems wholly dependent on fossil fuels (*system 1*) rises in direct proportion to increases in delivered fuel cost. However, the introduction of modest levels of renewable energy resources (*system 2*) reduces the influence of fuel cost on the total cost of energy (CoE). Initially, the CoE for such systems is more expensive due to the higher cost of producing energy from renewable energy technologies (at current market costs). As fuel costs increase, the economic viability of renewable energy technologies also increases, until they represent the more cost-effective solution. This is illustrated by comparing the CoE for systems 1 and 2 at point X, and the relative savings that could be achieved at times of higher fuel costs from an initial investment in system 2 (at point X').

Increasing the proportion of renewable energy in a system (*system 3*) further decreases the influence that fuel costs have on total CoE, although this benefit is tempered by higher initial energy costs and a proportional increase in the level to which fuel costs must rise before the system presents a CoE competitive option (shown to occur at point Y).

The ultimate extension of the replacement of diesel fuel with renewable energy resources is shown in *system 4* – a 100% renewable energy system. This system is wholly independent to changes in diesel fuel cost, but results in significantly higher energy supply costs due to the high capital investment required to produce and store adequate renewable energy supplies, including the likely use of innovative hydrogen technologies for energy storage.

At sufficiently high fuel delivery costs (point Z), the 100% renewable energy system becomes competitive with systems that are absolutely influenced by fuel prices rises (system 1), highlighting the economic merit of renewable energy resources at times of higher fuel costs. However, the 100% renewable energy system remains uncompetitive when compared to other systems that also use renewable energy resources.

System 2, with a relatively low level of renewable energy use and relatively high dependence on fuel prices becomes uncompetitive at moderately higher fuel prices (point A). In contrast, a system with high levels of renewable energy use but some dependence on diesel fuel (system 3) remains the most competitive option until significantly higher fuel costs occur.

The long-term competitiveness of hybrid solutions such as system 3 is illustrated by the intersection point of systems 3 and 4 exceeding the range shown in the graph and occurring at much higher energy costs. The reasoning behind this relationship, at least for the West Nordic communities considered, relates to the very high costs associated with designing self-sufficient energy systems that utilise only renewable energy resources.

For such systems, the inclusion of adequate safety factors for energy supply requires heavy investment in energy generation and storage infrastructure that may see little service during the life of the system. As renewable energy technologies, and associated storage solutions such as hydrogen, are comparably expensive forms of energy generation, their application as under-utilised infrastructure significantly increases the total cost of energy systems.

As an added complexity, the novel nature of using 100% renewable energy systems for applications such as community power systems generates additional costs. In contrast, the use of hybrid renewable-fossil fuels energy system designs, such as system 3, provides a cost competitive path to maximise the benefits of renewable energy resources and conventional fossil fuel systems. The general operating expenses of energy systems can be insulated against fossil fuel prices by using high levels of renewable energy resources, yet the costs of providing adequate system stability and security can be also minimised through the use of proven and low cost infrastructure operating on fossil fuels. The relatively low utilisation of the fossil fuel infrastructure contributes to reducing the influence of fossil fuel costs on the total cost of energy for system.

The clarification of this relationship between renewable energy use and cost of energy is one of the most compelling outcomes from the West Nordic project, indicating that the introduction of renewable energy technologies at low to high, but not absolute, levels of utilisation is the most cost-effective strategy for stabilising energy costs in the near to medium term.

The project report concludes that the introduction of renewable energy technologies will initially increase energy costs but will result in improved control over energy costs and reduce the impact on operations of surges in fuel price. Aiming for complete use of renewable energy (i.e. no fossil fuels) is very expensive and is not competitive until fuel costs are very high, but substantial improvements in operating costs and budget control can be achieved through high penetrations of renewable energy technologies into hybrid diesel systems.

Moving beyond the lessons offered directly from the West Nordic project, analysis of trends in the technology development markets, including renewable and hydrogen energy technologies, suggests that the relatively high cost of energy generation from novel energy technologies will decrease in the future with growing maturation of the technologies and markets. These cost decreases will influence the trends presented in the graph in proportion to the level of renewable energy technologies used by the different systems.

As these technologies mature, options such as system 4 will become increasingly cost-competitive, shifting the intersection point Z to the left. Similarly, hybrid solutions with high renewable energy use (system 3) will also become increasingly cost competitive relative to systems with high diesel dependency (system 1), while maintaining some cost advantages over solutions such as system 4.

Ultimately, the emergence of mature renewable energy technology markets and products, the accumulation of practical expertise with the design and operation of energy systems with high levels of renewable energy use and the increase in cost of fossil fuels will provide economic motivations and practical pathways for the development of 100% renewable energy systems. However, for the short to medium-term future, experiences such as those developed through the West Nordic project suggest that hybrid energy systems with high penetrations of renewable energy resources remain the most competitive pathway to reducing the vulnerability of communities to volatility and increases in the costs of conventional diesel fuels.

The results from the West Nordic project relate to the activities of Antarctic communities to introduce sustainable energy technologies in a number of ways. The results illustrate that a range of issues are shared between Antarctic research communities and other communities around the world. The results from the project are also of value to Antarctic communities as they can provide guidance for the development of long-term goals for Antarctic energy systems, based on the economic considerations that this research has shown are critical in influencing current and future decisions about energy infrastructure.

The existence of clear links between Antarctic communities and other energy users with interests in sustainable energy hydrogen energy technologies, as demonstrated by the seven projects identified above, suggests that all the communities involved would benefit from greater involvement with other communities with similar interests.

Due to the differences in location, capability, culture, finances and so forth between communities around the world, each community would have different strengths and weaknesses with regards to adopting new energy technologies such as hydrogen. Antarctic communities, for example, have some of the world's highest energy costs and a high degree of technical capability to adapt to new technologies.

Antarctic operations could therefore benefit the broader global energy using community by serving as early adopters for relatively expensive sustainable energy technologies. However, the government funded and bureaucratic nature of Antarctic operations or the physical elements of the environment may reduce the relevance to other communities of solutions developed in Antarctic in other areas of importance (e.g. community consultation methods or charging for energy services).

For the Australian Antarctic community specifically, the existence of these clear links suggests that development pathway for hydrogen use in Antarctica should include much greater involvement with other relevant markets and leverage the relative advantages of each of those markets to a common advantage. The relevance of activities in Antarctic to other programs around the world could also be used, if desired, to secure additional funds for energy system developments in Antarctica on the basis that the results will be transferable elsewhere.

9.4.6 Analysis of the research methodology:

The component of the research thesis addressed in this chapter had four specific goals that related to the non-technical issues surrounding hydrogen energy use in the Australian Antarctic program.

Developing a research methodology to capture the information required to address these goals was a challenge as very few examples existed for conducting such an analysis either with hydrogen energy technologies or with Antarctic communities. The methodology developed used three different techniques to engage with a variety of stakeholders and at varying levels of intimacy. These techniques included *Informal interviews and discussions, Formal interviews and questionnaires* and *Active community involvement.*

This methodology was successful in enabling adequate access to the necessary stakeholders in the community and providing appropriate forums to capture the information needed for the research. Informal interviews and discussions, for example, were used to gain a broad understanding of contemporary issues and attitudes within the communities. The meetings also helped to establish working relationships with a number of key stakeholders, which proved valuable in gaining more complete and open responses on potentially sensitive issues. The formal interviews and questionnaires enabled a formal social science style research program to be performed on a carefully selected group of participants to secure highly detailed and relevant information. The "active community involvement" component enabled the development of an informal and 'grass roots' understanding of the communities. It also secured the interest and support of the communities and their subsequent participation in the more intrusive and formal components of the research program.

In some regards, the scope of the research and methodology was too successful as an excess of information was eventually collected than that required for the amount of work required for this component of the research program. As noted in the results section, the subsequent presentation of the results required a hyper-summary of the materials collected in the three methods.

Some informal outcomes from the research also indicate that a different approach would be required to get truly accurate responses to particular questions about Antarctic energy systems and policy. For example, during the formally structured interviews with voluntary participants, a number of interview subjects requested an opportunity to provide supplementary "off the record" responses to questions that they also provided a different answer to on the record. These participants could have elected to not answer the question(s) under consideration, but instead felt compelled to provide both recorded answers and more controversial private answers. Overall, the formal interview technique was effective in securing "on the record" comments from senior managers within the Australian Antarctic community and gaining access to their time. Such access was not possible with the more informal methods used in the research.

9.5 Conclusions

There is currently a limited understanding of the general issues associated with the sustainability of energy services within the Australian Antarctic community. This is in alignment with awareness levels in the broader community. This lack of awareness extends to the need for and the complex details associated with the use of energy storage technologies such as hydrogen.

The strongest driver for Antarctic communities to begin engaging with technologies such as hydrogen is the rising economic cost of conventional energy systems. Other issues such as the limited operational performance, security of supply, and environmental impact of conventional systems are also important motivators.

The most significant barriers to the introduction of hydrogen technologies are the limited awareness of energy issues, the limited capability (and motivation) to adequately assess alternative energy supply options such as hydrogen, the lack of long-term strategy to ensure the sustainability of the community's energy services, and the limited proven viability of hydrogen technologies in the polar environment.

Suggested actions for the Australian Antarctic community to address these barriers include:

1. Raise understanding and awareness of the energy-related threats that the Australian Antarctic community will face in the future.
2. Improve the community's capability to assess alternative energy supply options. Collaboration with other parties who have similar interests in sustainable energy systems for remote communities is strongly recommended.
3. Develop a comprehensive and documented energy strategy with due consideration of the capabilities, values, external factors, and opportunities of the community and the full support of the community decision makers. This would include developing an agreed position on motivations for and extent to which the AAD would pursue alternative energy technologies in a fixed time frame, and the characteristics of solutions that would be sought. Within this framework, internal resources could be optimised to deliver the desired solutions rather than lobbying for action and resources for piece-meal projects as has occurred with the wind turbines at Mawson Station. The framework would also provide a more consistent environment in which long-term collaborations with external parties could be developed. Many issues beyond the technical viability of energy solutions will need to be considered.

The concept of using hydrogen technologies specifically as enabling components of more sustainable energy systems is in alignment with principles of the Australian Antarctic community. The technologies under consideration, and the approach suggested for the evaluation and implementation of the technologies, are appropriate. This view is supported by factors such as the principles of the Madrid Protocol in the

Antarctic Treaty System and the AAD's objective of being a leader in the use of environmental practices n Antarctica. Consideration of hydrogen is also in alignment with concerns about existing economic pressures on energy services, although hydrogen is not the most cost-effective solution at the present time. Hydrogen technologies also fit well with the changing strategic directions for logistics support in the Antarctic community.

In terms of accessing and implementing hydrogen technologies, the AAD needs to recognise that it is a significant and novel problem and that many changes will be required. The community must understand the full nature of energy-related threats that they face, and therefore needs a better understanding of how energy is used in current operations; the changing situations in energy supply trends, and the potential solutions that are relevant to their current and future activities. This will require more resources than currently available, and a change in behaviour with respect to 'research' in engineering issues, including greater engagement with external parties and the studying/trialing of options. Starting with smaller systems will be a key element of dealing with these many issues. The sharing of common issues with other communities around the world who have interests in hydrogen energy systems for remote regions should be used to increase the AAD's skills and knowledge about hydrogen technologies and their implementation and use in the field.

There are opportunities emerging to take very positive steps with respect to energy systems (e.g. development of the air transport network) and some characteristics of the Antarctic community are advantageous at this point in history for the development of alternative technologies could be leveraged to their advantage. The characteristics could be used to reduce the burden on the community, improve their ability to evaluate and access appropriate solutions and insure their energy systems for future events.

The multi-faceted approach to engaging with the community under consideration was successful in gaining the information required for the research. The large amount of material collected suggests that further work could be undertaken to detail a more comprehensive picture the community-related issues that would influence the development of implementation strategies for hydrogen technologies. The change in several key factors observed in the community over the course of the research, such as awareness of energy issues or environmental considerations, suggests that a follow-up research project would be required as some of the information collected in this research would already be out of date. Although the use of three techniques was successful in gaining access to a wide cross-section of the community and specific stakeholders, the desire of some participants to offer differing formal and informal responses in the structure interviews and questionnaires suggests that a revised interview approach is required to accurately and appropriately capture all responses within the formal research program.

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Chapter 10. Integrated Analysis and Discussion of Results

This chapter evaluates the outcomes of the three different sections of 'experiments' undertaken in the thesis, identifying the cross-cutting themes and key outcomes for the research. The discussion builds on the detailed analysis of the specific results completed independently in each of the three sections.

The specific research tasks defined for the project were:

1. To conduct a comprehensive evaluation of the roles that hydrogen energy technologies can play in Australian Antarctic operations, specifically when coupled with renewable energy technologies.
2. To perform a detailed engineering analysis of the technical viability of using hydrogen technologies for large applications in partnership with renewable energy technologies. The analysis should aim to be as 'real world' as possible to provide the AAD with highly relevant information to guide their future ambitions with Mawson station. The analysis should subsequently indirectly test if and how such real-world analyses can be conducted at the present time.
3. To engage with the Australian Antarctic community to identify and understand the non-technical issues associated with the evaluation and implementation of hydrogen technologies, and to enable assessment of the appropriateness of hydrogen technologies for the community.

10.1 Recurring themes in the research

Analysis of the results for each of the three components of research reveals nine recurring or cross-discipline themes:

1. The existence of a wide range of potential applications and roles for hydrogen technologies in Antarctic operations.
2. The existence of a wide variety of combinations of technologies and subsequent approaches to meeting energy demands that are enabled through the use of hydrogen technologies.
3. The importance of understanding current and future energy needs, the supply options that are available, and methods to identify appropriate solutions.
4. The limited capabilities of hydrogen technologies at present (however, the rate of development is rapid).
5. The significant influence of economic issues on energy systems.
6. The likely impacts of social issues on proposed or considered changes to energy systems.
7. The fact that experiences with sustainable energy solutions in Antarctic operations may be usefully applied to other communities around the world.
8. The need for an initial focus on the development and use of small-scale energy systems, even if larger-scale applications of hydrogen technologies are sought in the long-term.
9. The need for change management strategies to facilitate the evaluation and implementation of new energy technologies.

Each of these themes is examined in greater detail in the following sections.

10.1.1 The wide range of potential applications and roles for hydrogen technologies in Antarctic operations

Chapter 3 in the literature review examined the general characteristics of hydrogen technologies and the subsequent roles that the technologies could play in modern energy systems. Chapter 7 subsequently explored these general roles for hydrogen technologies as related to the different types of activities undertaken within the Australian Antarctic community. The general reviews and specific case studies indicated that hydrogen technologies had valid applications in almost all aspects of operations, from running the large stations to meeting the needs of small hand-held devices. Hydrogen technologies can subsequently have many possible roles in Antarctic operations. The energy system modeling analysis supported this assessment with a higher resolution analysis of the roles that hydrogen technologies could play within a specific application, namely running a large station with a high penetration of renewable energy technologies. The research on community engagement revealed that energy system users could conceive a wide range of potential applications for hydrogen technologies based on their demands for energy services, even though they had limited knowledge of the capabilities of hydrogen technologies.

10.1.2 The wide variety of technology combinations and approaches to meeting energy demands that are made possible with hydrogen technologies

The results from the roles analysis in Chapter 7 also illustrated that the inclusion of hydrogen technologies in energy systems enables a wide range of technology combinations, and subsequent styles of energy systems, to be used in meeting energy demands in Antarctic operations. For example, fuel cell and modified diesel electric generators can work independently, or in collaboration, to meet the energy needs of a field camp using hydrogen fuel. Similar configurations can be used to meet the energy needs of larger permanent stations. In either case, the hydrogen components could also be integrated with wind or diesel-based power systems. In this manner, the same components are being used in a variety of roles, or a specific energy demand can be met using a variety of hydrogen components and system configurations. The analysis also considered how the enhanced capabilities of hydrogen technologies in the future could potentially be used to meet Antarctic energy needs in an even wider assortment of methods, and proposed routes by which hydrogen technologies could be incrementally introduced into operations. Chapter 8 examined this possibility in much greater detail, with the simulations considering several different system configurations. The analysis of possible links between Antarctic operations and the use of hydrogen in other applications in Chapter 9 revealed how similar projects around the world are also meeting the same application with a range of hydrogen and energy system configurations.

10.1.3 The importance of understanding current and future energy needs, the supply options that are available, and methods to identify appropriate solutions.

A comprehensive understanding of current and future energy demands is important from a technological perspective as such details are essential for defining the performance characteristics of energy systems. This research has shown that the details are also important for a number of other factors that influence the identification of truly appropriate energy solutions, and achieving effective, safe and efficient progress towards accessing those solutions.

The literature review began with an examination of the broad issues surrounding the sustainability of energy systems and the options available to improve the performance of energy systems, including basic approaches to improving efficiency and more innovative and sophisticated solutions such as the storage of excess renewable energy as hydrogen. Chapter 3 reviewed the current status of energy systems in Antarctic operations and, in the context of the Australian community, the need to evaluate future steps that include hydrogen technologies as a range of simpler efforts to improve the sustainability of energy systems had or were being explored. Chapter 4 reviewed the need for and methodology of selecting appropriate energy solutions and the associated need to understand a community's current and future energy needs and their capability to accept and integrate new technologies. Chapter 9 subsequently evaluated the appropriateness of hydrogen technologies within the cultural and capability context of the Australian Antarctic community and determined that the consideration of hydrogen technologies is appropriate.

A relevant outcome from the exploration of hydrogen technology roles and technology combinations in Chapter 7 is that of the many possibilities, some must be better suited to the community needs and capabilities at the present time. Different solutions may become more appropriate in the future, but the accessibility of the solutions may be dependent on the sensible selection of specific solutions in the short-term. Chapter 8 examined this issue in greater detail, reviewing how different decisions regarding energy demands can have a significant effect on the design parameters of energy systems. The concept of 'energy demands' however, was shown to encompass more than power requirements but also economic and environmental factors or the utilisation of infrastructure and the safe and effective introduction of new technologies.

In communities and operations with a range of energy uses, such as the transport systems, permanent stations and field camps of Antarctic communities, a detailed understanding of energy needs, appropriate solutions and the supply options that are available must have a significant influence on long-term management decisions.

Decisions on issues such as the management of significant assets (permanent stations) or the planning and financing of field science programs in the short- and long-term naturally include factors related to energy use, either in terms of the purchasing of fuel supplies or plant and equipment. An understanding of future energy needs, the sustainability of energy systems, the likely influence of external factors such as international fuel prices, and the capability of the community to identify and implement desirable alternative solutions should therefore contribute to the decision-making process.

Chapters 4 and 7 explored energy usage in the Australian Antarctic program and illustrated how renewable energy technologies can reduce the demand for fossil fuels at the stations by hundreds of thousands of litres per year. A reduction in fuel demand would also improve the environmental performance of a station, and reduce the impact of fuel price rises on the total operating costs of the station. Understanding that such opportunities are possible is important for community management, but an understanding of the issues involved is also important for decisions on when, where and if such solutions should be pursued. The significance of understanding such issues in detail is reviewed in the West Nordic project example in Chapter 9 which illustrated that the proportional contribution of energy from renewable and imported fuel sources for a remote community can be optimised from an economic perspective [1].

To look at Antarctic energy issues and their impacts on other elements of operations from a broader perspective, the other significant area of energy use in the Australian community is in the shipping transport network. The annual consumption of fuel in shipping is approximately six times that of the consumption for each of the permanent Antarctic stations, or twice the combined consumption of the three stations. On average, the fuel used in a single return journey to Antarctica is roughly equivalent to the operation of a station for an entire year. For a number of reasons, efforts to reduce the net emissions from fuel consumption by the Antarctic community or to reduce the money spent on energy should perhaps focus on the Antarctic shipping program. Removal of a single voyage per year would have the same effect as closing a single station. Alternatively, improvements in the efficiency of energy usage by the ships used in the program could have more substantial impacts on total fuel usage than efforts at one or all of the stations. If the community management needed to decide on priority areas for seeking improvements in energy system sustainability (or economic performance), an understanding of the community's usage of energy and ability to make changes to energy systems in stationary applications and the shipping program would be important.

This study has not evaluated the potential to make improvements to energy usage in shipping and so can only assist in providing understanding of the opportunities for changes to the energy systems used on the continent. A major reason for not considering energy use in shipping, however, was the very limited opportunities to make changes to the power plants of existing vessels and subsequently the limited capability of communities to make changes in their energy use. As demonstrated by this study, the flexibility of the energy systems used in other aspects of Antarctic operations make them far more suitable for the integration or exchange of novel energy technologies such as hydrogen.

10.1.4 The limited capabilities of hydrogen technologies at present but the rapid rate of development

A recurring theme in the research was the presently limited capabilities of the many tools and technologies associated with hydrogen energy. For example, very few hydrogen energy components are commercially available at present. Of the components that are available, such as small-scale electrolysers or fuel cells, the prices are high and the components are relatively inefficient. In addition, very few resources are available for supporting the technologies, or even enabling effective analysis of energy system designs. Few training programs currently exist, for example, for technicians to service fuel cell systems. Also, the energy system modeling tools currently available cannot integrate combined heat and power system designs into wind-hydrogen systems. Although the current capabilities of hydrogen technologies are limited, the success of systems such the PURE [2] and Utsira Island [3, 4] projects reviewed in Chapter 9 is confirmation of the viability of the technologies and tools.

In addition to having achieved the necessary minimum levels of capability required to enable viable energy systems to be developed, implemented and operated, hydrogen technologies are also displaying a rapid rate of continuous development. This development will address many of the issues faced by hydrogen technologies and improve their capabilities over present levels, making them even more attractive to remote communities. The rapid rate of development, and therefore changes in the capabilities and availabilities of hydrogen energy technologies, further emphasizes the need for communities to maintain an awareness, if not a detailed understanding, of their energy needs as related to the capabilities of the various technologies that could be utilised.

10.1.5 The significant influence of economic issues on energy systems

As with almost all issues in modern society, economic considerations have emerged in all facets of this research. On the most basic of levels, energy services cost money and factors such as supply and demand of fossil fuels or environmental protection requirements are driving up these costs. For communities in remote regions, where additional energy must be used to transport energy resources, these increases in energy costs are compounded. The introduction of changes to existing energy systems also costs money, but some changes have the potential to actually save money such as through improvements in efficiency or the harnessing of cheaper energy resources. The use of local renewable energy resources in Antarctica, for example, can in some circumstances provide energy services at a lower economic cost than the delivered price of imported fossil fuels. Hydrogen energy technologies, although described as critical components for more sustainable energy systems based on renewable energy use, are currently very expensive for almost all applications. Their use, however, has the potential to enable long-term independence from the rising economic and environmental costs of fossil fuel use. The variety, versatility of application and rapid rate of development of hydrogen technologies also makes it difficult to make general statements about their economic competitiveness relative to more conventional technologies. The HSAPS project reviewed in Chapter 9 identified many of the challenges associated with obtaining data about hydrogen technologies, as well as useful information and longer-term pricing predictions [5].

Determining the true cost of energy services is also a complex issue beyond determining the specific cost of technology components. Indirect and operating costs must also be considered, such as fuel consumption, delivery of fuel, access to service infrastructure or trained operating personnel. Understanding the full scope and magnitude of such costs is important for communities, especially if they are deciding if and when they should make changes to their energy services, and particularly with the introduction of new technologies such as hydrogen.

This research has considered the significance of economic costs for energy services from a different perspective with regards to the use of hydrogen technologies in Antarctic operations. Specific economic costs of hydrogen systems have not been determined due to the higher priority of needing to understand what roles hydrogen technologies can and should play in operations. The complexities involved in determining specific component costs, as illustrated by the two years invested in the HSAPS project, also suggested that the research effort could be better invested in other areas [5]. As an alternative to developing specific economic costs, this research has aimed to develop strategies and information to help communities improve their understanding of the broad issues influencing the costs of hydrogen energy technologies and their inclusion in energy systems. In general, fossil fuel costs are anticipated to rise and hydrogen costs are expected to drop as time progresses. At the time of writing, these changes are occurring at a rapid rate. At some point the relative costs of energy from the competing technologies will be comparable, and the specific timing of the intersection point will be different for different communities, the technologies they are considering and the applications. Communities should therefore undertake detailed economic analysis of specific applications only when they are seriously evaluating a specific situation, and should be prepared to repeat the evaluation after a suitable time period if conditions are not favourable at that time.

10.1.6 The impact of social issues on potential changes to energy systems

A major component of the research program focused on exploring the impact of social issues on the development of more sustainable energy services for remote communities. The motivation to do so was based on examples from energy system projects around the world, including the development of wind turbines at Mawson station, which had been negatively impacted by issues with the energy system configurations that were non-technical in nature.

The general analysis of energy issues in Chapter 2 reviewed how modern energy services had failed to meet the needs of a large proportion of the global population. Although social issues had not impacted the provision of services to approximately two-thirds of humanity, issues within the poorer communities had prevented the extension of those same energy services, even though access to energy services has been identified as a fundamental foundation for modern development. In the context of deploying renewable energy technologies and hydrogen systems, examples are emerging of systems that never commence, are delayed and changed, or eventually fail due to negative social issues. Even within existing programs to develop more sustainable energy services for Antarctic communities, social issues have had negative impacts on projects that are technically and economically viable.

Chapter 4 reviewed the current status of energy services within the Australian Antarctic program. This included the commissioning of two wind turbines at Mawson station based on a solid technical evaluation of the viability of the technologies and detailed but conservative analysis of the economic savings and environmental benefits that the use of local wind energy resources could offer. The wind turbine project was cited as a positive example of the progressive attitude of the Australian Antarctic community towards the consideration and introduction of alternative and more sustainable energy technologies.

There is, however, another, less public and less factual side to the wind turbine project story that illustrates the influence of social issues over seemingly rational and positive technical considerations. The Mawson turbine project was originally designed to utilise three 330-kW wind turbines, and was subsequently assessed and funded on this basis. The station energy system was upgraded to accommodate three turbines. Foundations for three turbines were constructed onsite, and three turbines were ultimately purchased and transported to Antarctica. Unfortunately a disruption to the shipping schedule, as often happens with Antarctic operations, cut short the time available to install the three turbines in the nominated summer period. Two turbines were successfully erected and commissioned, and plans were developed to install the final turbine in the following year. Equipment, including a ~$1 Million vehicle crane for erecting the turbines, was kept at the station with the uninstalled turbine.

It appears that the funds remaining in the project account were subsequently 'absorbed' into general budget of the Australian Antarctic Division on the basis that a proposal to erect the third turbine would be assessed against other necessary initiatives in the coming years and funded when 'appropriate'. Three summers passed without the turbine being installed, despite the successful commissioning of the two operating turbines and solid evidence that they were offsetting significant volumes of fossil fuels. The AAD also saw the success of the turbine project as a means to generate a profit stream through the sale of credits for the 'green power' generated by the turbines with a ten-year contract with an Australian bank [6].

In late 2006, a swift decision was made by senior management to load the third turbine and vehicle crane onto a cargo vessel that was at the station for return to Australia for the subsequent sale of the assets. A number of reasons were cited to those who questioned the move, such as an inability to bring the vehicle crane back after the 2005/6 summer as the multi-year charter of the cargo vessel was to expire and no replacement vessel would be chartered (due to the expected commencement of the air transport project). The Christmas holidays of senior AAD personnel made discussion of the matter difficult, and frantic efforts were made to modify the plans and keep the turbine at the station. Personnel with interests in the hydrogen demonstration project even contacted the author (in Denmark) to determine if the removal of the turbine would have a significant effect on the future operation of the station with a larger wind-hydrogen system (a concept that other elements of the Australian Government were enthusiastic to support financially). An adequate defence was not mounted and the turbine was returned to Australia for sale, much to the disappointment of the project team and the turbine manufacturer who had made a significant personal investment in the project.

It is the author's opinion, based on private discussions with key decision-makers within the AAD over the course of the research, that elements of the AAD management were never fully supportive of the turbine project and were influential in reducing the scope of the project and resisting efforts to spend further funds beyond the initial commissioning phase. Results captured through the community consultation process presented in Chapter 9 confirmed that some elements of the AAD community viewed the commissioning of alternative energy technologies as beyond the scope and purpose of the AAD, and therefore not a valid use of resources even if the turbines were funded externally and provided economic savings for the community. The potential to secure additional funds through the sale of the third turbine and the crane was more attractive to management than the alternative of spending money to install the turbine and ultimately reduce fuel bills in the long-term.

This relevant but little-known facet of AAD operations also suggests that the AAD's attitude towards renewable energy (and perhaps hydrogen) use is becoming more conservative in spite of these renewable energy initiatives. A similar example of how energy projects in Antarctica can be negatively influenced by social issues is the history and current status of the Hydrogen Demonstration Project for Mawson station. The project has been cited numerous times as a positive example of the progress that is being made in evaluating and learning about hydrogen energy technologies and their application in an Antarctic operations context. However, as a party intimately involved in the genesis of the project, the finer details to the development of the project provided the author with a number of excellent lessons and experiences in the power of social issues.

For many communities with interests in developing more sustainable energy solutions, the announcement of the project and funding to investigate novel energy technologies that could enable further independence from fossil fuels could be seen as a positive situation - particularly if the project would enable greater use of an already established and publicly-praised wind-energy project. However, with the Mawson Hydrogen Demonstration Project, the announcement sparked a degree of controversy and angst within the AAD's management structure. The information is not public knowledge, but at the time of the announcement the AAD management exhibited both anger about the initiative and reluctance to embrace the project. As a key stakeholder in the process, it is the author's opinion that the attitude was related to a perceived 'turf invasion' by another government agency (the AGO) when it proposed and funded a project related to Antarctic operations – an area of government activities that is generally the sole responsibility of the AAD. The enthusiastic response of the Minister to an innovative and attractive renewable energy project with an Antarctic focus that the AAD had not championed may also have contributed to the frustrations of certain members of the AAD management team.

Two other reasons for the 'restrained' response of the AAD towards the hydrogen project were confidentially proposed at the time to the author by parties involved in the decision-making processes. The first reason was the conflicting nature of the project with other closely-held objectives within the management team. In essence, a plan was being developed to effectively close one of the three permanent Antarctic stations operated by the AAD in an effort to cut costs and achieve more scientific outcomes with the same operating budget (and to ease the impact of rising fuel costs for operations). The station under consideration was Mawson, and attracting the Minister's attention for a high-profile (albeit small) project that would involve other government departments and ministries was seen to be a step in the wrong direction. Information from confidential sources later indicated that the station closure initiative was ultimately quashed by senior members of the government based on a range of considerations. The author believes that the Mawson Hydrogen Demonstration Project had little real impact on the station closure initiative and its subsequent demise. The second reason proposed was that certain members of the AAD management team did not support efforts to introduce renewable energy technologies into the AAD's operations, seeing them as a poor investment and not contributing to the core goals of the AAD. Apparently such issues had been exhaustively addressed during consideration of the wind turbine project for Mawson, and securing the final approval had proved a challenge. The perceived extension of that project with the hydrogen demonstration represented a further deflection of AAD resources away from the Division's 'core business'. These factors illustrate that social rather than technical issues were highly influential in both establishing the initial support for the demonstration project and influencing the way in which the project was ultimately handed by the government's 'lead agency' for Antarctic affairs.

Regardless of these issues, the Mawson Hydrogen Demonstration Project did commence, and is currently operating in Antarctic and producing hydrogen 'fuel' from excess wind energy. What the AAD does with the information it learns and the steps it takes at the completion of the project should indicate the management team's true feelings towards the project and what the future may hold for such initiatives. The status of the project, as of November 2007, further illustrates the influence of social issues on projects. Additional funds were secured from external sources to purchase a small fuel cell for use in the polar environment. The component was installed and ready for operation at the station in a non-critical role as an initial test and demonstration of its effectiveness before being transported to a nearby field camp for further service. The trades staff who were to be responsible for the operation and maintenance of the fuel cell, however, refused to interact with the device without access to relevant industry standards. As a consequence, the component is currently not in service and the project is at risk of collapsing. The result could have been very different if the AAD had sought to effectively engage with those trades staff prior to their deployment to Antarctica to brief them on the project ambitions, safety and risk assessment outcomes, and the current status and availability (or lack of) relevant standards for hydrogen energy use as a fuel. However, at the present time the investment of over $1 million in the project is being severely impacted by a minor social issue.

10.1.7 The relevance of linkages to other communities around the world

The research has determined that, in the broadest terms, there are a range of basic issues shared between Antarctic communities and other communities around the world relating to the pressures and challenges of seeking sustainable energy solutions. The potential solutions are common, and many of the technical factors are common too. On this basic level, experiences and solutions can therefore be shared between the different communities. The wind turbines used at Mawson station are an example of the potential for the development and sharing of solutions by remote communities around the world. The original concept for the wind turbine system and associated energy system components was based on hybrid wind-diesel energy systems operating in remote communities in Western Australia. In order to use conventional wind turbines in the harsh and exceptionally cold Antarctic environment, however, specific modifications needed to be made to the turbine designs such as to prevent snow penetration.

Clear links exist between Antarctic operations and communities in the Arctic region, where physical conditions are similar and remote locations, sensitive environments and high energy costs are also motivating efforts to develop alternative energy systems. Antarctic communities can benefit from these efforts. For example, the experience and knowledge that the wind turbine manufacturer developed with the Mawson project was applied in developing wind turbines suitable for use in more extreme environments in the Arctic region. The same turbine manufacturer subsequently supplied a larger but similar turbine for the wind-hydrogen demonstration project developed on Utsira Island in Norway [3, 4], and this project served as an inspiration and effective demonstration of the viability of the system for the proposal of the Mawson Hydrogen Demonstration project. The modeling tools used in Chapter 8 of this thesis were based on resources developed to design the Utsira island project. Results from the HSAPS study on Arctic communities were also used in the models [5]. Outcomes from the West Nordic Project [1] regarding the relative economic benefit of different levels of renewable energy penetration in diesel fuelled systems were also shown to be highly relevant to the evaluation of system performance parameters investigated in the modeling chapter.

Efforts to evaluate and introduce hydrogen energy technologies in Antarctic operations are also relevant to other communities in a broader context – the publicity generated by hydrogen demonstration projects can inspire interest in other communities, just as the Utsira island project was an inspiration for the Mawson project. The funding provided by AGO for the Mawson Hydrogen Demonstration Project was partly due to the potential for the project to serve as an inspiration for other communities [7].

A proposal was presented in the literature review that Antarctic communities have greater economic and technical capability to engage with new technologies and stronger environment-linked motivations to pursue sustainable energy solutions relative to other communities. This would make them well suited to serving as early market adopters (EMAs) for hydrogen energy technologies. Such action would provide a market for viable technologies that are ready for commercialization but are unable to compete with existing products in conventional markets. Stimulation of the market would drive further development of the technologies, resulting in performance improvements and reductions in cost that would make them more competitive for other customers. The assessment is accurate in regards to the greater economic and technical capability of the communities. However, the community engagement work presented in Chapter 9 indicates that environmental issues are not as significant a driver as expected.

There are also constraints placed upon Antarctic communities that would make it difficult for them to engage with hydrogen technologies even with higher energy costs, and reduce the relevance of them serving as EMAs for broader markets. The very remote and harsh location results in expensive and challenging testing environments. The risks of using pre-commercial technologies are also higher for the users due to the extreme environment. The community is generally conservative in nature, government-run, bureaucratic, and not experienced in the testing and evaluation of novel energy technologies. In a wider geographic context, support for evaluation of novel energy technologies remains limited as there is little experience in Australia with hydrogen energy technologies.

Another consideration when evaluating the value of Antarctic communities as EMAs for hydrogen technologies is the market size and market relevance. Antarctic operations are relatively small and specialized markets for technologies that can perform in very extreme environments. Although there is a commonality of need for more sustainable and accessible energy services with communities around the world, there is little relevance to the billions of people in the developing world who do not have access to modern energy services, aside from operating in remote and harsh environments.

Figure 10.1 provides a visual representation of the proposed relationship between market size and the potential viability of a community to serve as an early market adopter, based on economic capability. The developing world is the largest long-term market, but the communities have very little capability to access energy technologies. Antarctic communities, with their conditioning to very high energy supply costs, have the greatest economic capability to access but are very small markets. The middle ground is occupied by other niche markets such as the military, science programs, specialist tourism activities, and the telecommunications industry. These markets are more diverse in nature than Antarctic communities and larger in market size, but (as illustrated by the examples of relevant projects presented in Chapter 9) do have many characteristics in common with Antarctic communities including high energy costs, technical capabilities, sensitive environments, and operational needs that cannot be met by conventional technologies.

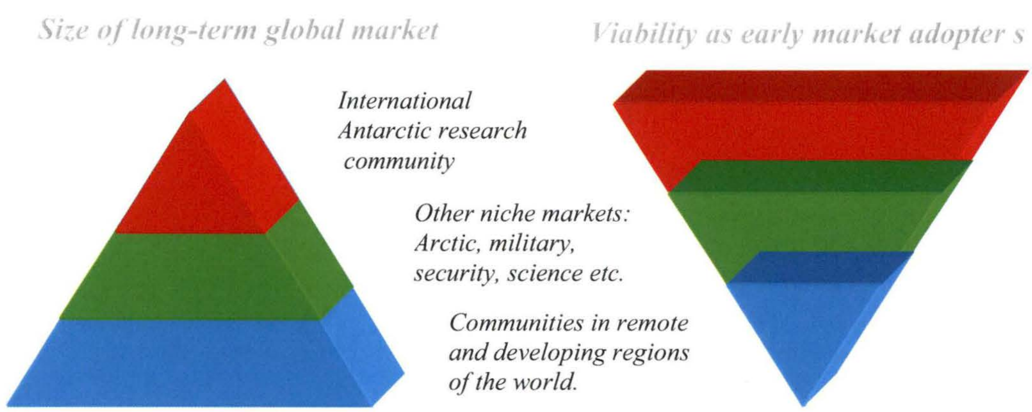

Figure 10.1: comparison of relative market size and viability as an early market adopter for Antarctic communities and other energy using communities around the world.

Based on an analysis of market size, economic capability, and other issues that influence the viability of markets serving as early adopters, Antarctic communities do have attributes that make them attractive and they could play valid roles in enabling the development of sustainable energy technologies. However, some of the similar communities considered would be better suited as serving as EMAs from a global perspective. Communities, for example, that are more conventional in nature, situated in less remote locations, with more transferable operations and energy systems designs, whilst possessing as many of the characteristics as possible that make Antarctic operations attractive as EMAs. Antarctic communities could also benefit from engaging with these communities and gain from their experiences with hydrogen technologies. The investments by governments, industries and communities in the development of early markets for hydrogen technologies could also be achieved with favourable conditions for the development of EMAs but with reduced risk relative to using Antarctic communities as EMAs by focusing on these mid-range communities (the middle band in Figure 10.1).

The most logical candidates as EMAs status for hydrogen technologies based on these factors are communities and research bases in the Arctic region. They offer an ideal combination of remote, harsh and pristine environments with relatively skilled and capable communities (particularly at research bases) that are geographically close to major centres for education, research and technology development and commercialization. Nations in the Arctic region are generally economically prosperous and sensitive to environmental issues, and so have the capability and motivation to evaluate and implement more sustainable energy services. The Arctic nations are also generally active in the transfer of aid and development, including energy services, to developing nations and poorer communities. Solutions developed in early adopter communities in the Arctic region are therefore more likely to contribute to the development of sustainable energy solutions for the developing world than would solutions developed in Antarctica.

Based on this concept, an integrated Arctic-Antarctic development plan was developed that aimed to maximize the relative advantages of Arctic and Antarctic communities to overcome their individual and shared barriers to the development and implementation of hydrogen energy technologies (see Appendix 9 for further details). A key component of the proposal was greater targeted collaboration between energy-using communities in the Arctic and Antarctic, with Arctic communities as the key partners but recognizing the specialist contribution and greater economic competitiveness of Antarctic operations.

The project concept was founded on the need to improve linkages between communities, government (drivers for clean energy uptake by communities), energy researchers and energy technology providers to reduce the negative influence of social issues on the deployment of sustainable energy solutions in communities. This research project had indicated that technical solutions and funding sources were available for the evaluation and deployment of sustainable solutions, but a lack of awareness, skill and confidence within communities and poorly-managed social issues were the main barriers to progress. Improvements in communication were anticipated to enable the identification of shared areas of interest, collaboration on developing solutions to issues, and the education of stakeholders about drivers and barriers to implementation. The concept was presented in a number of fora and compiled into a comprehensive grant application to the EU under the FP6 framework in 2006 (The application was not successful as it did not contain enough 'science').

The proposal was revised and integrated with the skills of the UNEP Risoe Centre for Energy Climate and Sustainable Development for submission to the Nordic Energy Research organisation in late 2006. This application was successful and secured ~AUD$2 million cash and in-kind contributions from the funding agency and project partners to develop a network in the Nordic region focusing on sustainable energy technology transfer [8, 9].

The development of stronger links with other communities and organisations involved in the development and implementation of sustainable energy solutions will enable the Australian Antarctic community to more effectively evaluate and progress their own ambitions with regards to energy services. At the present time, very few links exist beyond those within the international Antarctic community. In some regards, this is a situation of "the blind leading the blind" as very few members of the community are actively engaged in evaluating more sustainable energy technologies – the Australian community considers itself a leader in this regard yet remains relatively isolated from non-Antarctic focused interests. Securing support for expansion of the networks will require a change in the mindset of the community members who do not believe that energy technologies relate to the community's activities. The precedents established with the Mawson wind turbine and hydrogen demonstration projects could be effective in this regard, but as detailed above, these projects also appear to have generated increased negative sentiment about energy issues with some key elements of the community. Even if links to external communities are developed or enhanced, Antarctic communities will still need to assess if, when and how they should actively engage with hydrogen technologies. An efficient approach in the short term could be to support the use of Arctic communities as early adopters, as they are the most comparable operations to Antarctic activities and have the greatest potential for effective transfer of solutions in the future.

10.1.8 An initial focus on the development and use of small-scale energy systems

A recommendation or observation that has emerged in all areas of the research is that remote communities should initially focus any efforts to evaluate and introduce hydrogen energy technologies on the use of the technologies in small-scale applications.

The analysis of roles for hydrogen technologies, for example, determined that there are many potential small-scale individual applications for hydrogen energy technologies. In contrast, there are only three possible applications of large-scale energy systems at the three permanent stations. The types of activities encompassed in the category of small-scale energy demands are also less likely to be adequately or optimally supported by conventional energy technologies. The introduction of hydrogen technologies would therefore have a larger impact on improving the performance of the energy systems for these applications. Small-scale energy demands are also more likely to be situated in very remote and undisturbed locations where the potential advantages of hydrogen technologies, such as reduced transport requirements and improved environmental performance, will be more valued.

In terms of the availability of hydrogen technologies for use by Antarctic communities, the most mature and rapidly developing categories of hydrogen products are those targeted at small-scale applications. In addition to enabling access to a wider range of more mature products, a focus on small-scale energy demands also makes hydrogen technologies more accessible to Antarctic communities in the near future. The use of small-scale components would reduce the complexity of integrating the technologies across the operations of the community, which will be important with their currently limited level of experience with hydrogen technologies. The purchase of smaller components also reduces the financial expense and risk involved in developing experience with hydrogen technologies in Antarctic applications. The modeling component of the research indicated that developing practical experience with the operation and integration of hydrogen technologies into Antarctic operations before making significant investments and infrastructure would be wise. An initial introduction to cheaper, smaller and less complex hydrogen energy systems would provide such experience and knowledge building. The systems could also be used to educate and engage with the broader community to confirm that the technology selections are appropriate for the community and to reduce the potential for non-technical issues to influence the development of sustainable energy systems.

As with the availability of hydrogen products for use by Antarctic communities, the broader market for hydrogen technologies on a global scale is aiming towards small-scale energy demands. This will influence the products that are available for use, but will also influence the types of knowledge and experience developed in the broader community that Antarctic communities can transfer to their own operations, or contribute their experiences to.

The current efforts within the AAD to demonstrate hydrogen technologies via the Mawson Hydrogen Demonstration Project are an effective application of these concepts. The project aims to utilise the generating capacity and support resources of Mawson station to produce hydrogen, but demonstrate the technologies in a smaller field camp. This strategy increases the exposure of users and highlights the capability to develop a transportable fuel from wind energy and replacement of a fossil-fueled generator with a clean and silent energy solution in a sensitive environment where noise and fuel contamination could have a critical impact on local wildlife. The existing use of a high proportion of renewable energy at the facility enables a strong demonstration of the future direction of Antarctic energy systems, including the greater flexibility required from energy system users when interacting with the energy services. The demonstration of a range of hydrogen technologies further increases the potential for dissemination of knowledge through the community and the collection of accurate feedback on the value of the solutions to users before committing the community to more substantial effort and investment.

10.1.9 The need for change management strategies

Antarctic research communities are facing a historically unique set of factors that are creating a demand for fundamental changes in their energy systems if their operations are to remain sustainable. These factors are also shared by all energy users around the world. They include the growing awareness and rejection of the environmental impacts associated with fossil fuel use and the unprecedented circumstance where global demand for liquid fossil fuels will soon exceed the practical (rather than artificial) limits to supply. The need for change is real and significant and will require substantial undertakings from the communities with changes to infrastructure, operations and behaviours to enable modifications to energy systems. The changes will also create opportunities to improve the performance of energy systems or the scope and focus of operations.

As with any ambition where the level of change required is significant and the associated risks and possible benefits are also significant, it is logical to develop well-considered strategies to direct, plan and evaluate the actions necessary to achieve the changes. In the context of changing the energy systems used by Antarctic communities to make them more secure, environmentally-friendly and cost-effective through the use of novel energy technologies such as hydrogen, the need to develop strategies has emerged in each component of the thesis.

Strategies are needed, for example, to ensure that solutions that are considered and applied are evaluated in terms of their true appropriateness for the community and not just based on technical or economic considerations. The many potential roles for energy technologies and associated technology configurations made possible by hydrogen technologies require some degree of prioritisation and selection to ensure efficient and effective efforts. As detailed in the energy system simulation component of the research, the technical issues associated with hydrogen systems can be complex. Strategies are needed to ensure that the community is able to access or develop the competencies necessary to enable such the use of such complex systems if required. As with all projects involving energy resources, there is also a high degree of risk embodied in making changes to energy systems. These risks need to be identified and effectively managed for the community.

The community engagement component of the research identified that addressing energy issues is not one of the core roles of the Australian Antarctic community. Management strategies are needed in such circumstances to balance the competing priorities within organisations and communities to ensure that sustainable ambitions are established and adequately resourced. The removal of the third wind turbine from Mawson station is a clear example of how projects that are peripheral to the core roles or values of a community can be impacted in the absence of clearly defined and resourced strategies for changes to energy systems.

A generic strategy and framework to guide remote communities in evaluating and implementing sustainable energy solutions, including the use of novel energy technologies such as hydrogen, is presented in Chapter 11.

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Chapter 11. An implementation strategy for Antarctic communities to adopt sustainable energy solutions

This chapter presents the framework for a generic 5-10 year strategy and action plan that can be used by Antarctic communities to increase the sustainability of energy resources at their stations. It also describes how to take action to understand energy usage at the stations and gain access to renewable energy resources for energy generation. The strategy is written for consideration and use by practitioners and senior management within Antarctic research communities, and so can be used as a stand-alone document separate from this thesis.

The strategy is developed from the perspective that very few Antarctic communities have significant experience with even basic sustainable energy technologies, and it therefore focuses on building initial skills, knowledge and experience. The methodology can also be applied for the evaluation and introduction of more complex energy technologies such as hydrogen for energy storage and transport applications. The strategy is also highly suited to transfer from the target audience of Antarctic research communities for application by other communities in isolated and harsh locations around the world, particularly communities in the Arctic who are dependent on fossil fuels for energy production and transport.

Six specific recommendations are derived from the strategy for Antarctic communities (and/or others) to consider today if they are motivated to access more sustainable energy services. After being developed for this research thesis, the framework was subsequently successfully applied in the creation a strategy for a member of the international Antarctic community as a research consultancy.

11.1 Understanding a station's energy demands

The use of fossil fuels (primarily diesel) for the generation of thermal and electrical energy at Antarctic stations is a significant component of the economic costs of operations, incorporating direct fuel purchase costs and the transport and delivery of fuel and infrastructure to remote sites. Growth in energy use and subsequently the operating cost of a station, and concerns about actual and potential environmental impacts, are prompting efforts to improve the efficiency of energy use and introduce alternative energy sources.

Understanding what energy resources are available at Antarctic stations, what they are used for and how they are supplied are key elements to achieving success in these efforts. Such knowledge is often captured through an "energy audit".

Generally little is known about the energy demands and generation performance of existing stations, aside from broad statistics such as fuel usage figures. It is strongly recommended that comprehensive data about energy generation and use for thermal and electrical loads be documented for stations. This information will serve as a foundation for improving operations and the effective long-term introduction of more sustainable energy solutions.

The capture of detailed knowledge of energy generation and use at stations would enable improved management of the station loads and generation resources, such as through peak load shedding, which would minimise the need for increased generation resources and enable improved efficiency of use of existing capacity and fuel. It would also enable effective evaluation and the introduction of renewable energy resources in the long-term. The introduction of a small proportion of renewable resources (e.g. 10% wind) to the generation systems would not have a significant impact on the operation of the existing generation resources relative to the optimum operating load of the generators.

It is recommended that Antarctic operators initiate new and specific projects to design, implement, manage and utilise comprehensive energy system monitoring programs for their Antarctic stations. If monitoring programs do already exist, these systems should be evaluated from the perspective of relevance of the data for effectively assessing energy use, quality of data collection, and management of the datasets to ensure consistency and quality.

Recommendation 1: develop a specific project for 'energy system monitoring' at Antarctic stations as quickly as possible (or review existing monitoring programs).

11.1.1 Components of energy system monitoring programs

The projects should have discrete components, which could be addressed as individual sub-projects. They include:

1. Review of the existing logging program & activities
2. Develop a 'load logging plan' to capture necessary information.
3. Initiate and manage the installation of the logging infrastructure.
4. Initiate a 'data management' project, specifying the collection, quality assurance, and cataloguing of data for later analysis.
5. Initiate a data analysis project, evaluating the data as required and recommending practical outcomes from initial data.

11.1.2 Proposed outcomes from energy systems monitoring projects

Proposed outcomes from such a logging project include:

1. Detailed understanding of energy flows on station.
2. Identify opportunities for:
    a. Improved efficiency of energy use
    b. Better management of peak loads (load shedding)
    c. Effective introduction of appropriate renewable energy resources (e.g. wind for electricity, passive solar heating etc)
3. Identify 'lost energy' resources.

11.1.3 Suggested elements of an energy mapping project

The recommended elements of the station operations that should be recorded in an energy mapping project include:

1. Identity of major electrical and thermal power demands
2. Detailed time-based (1hour -> 1 min) load on major demands
3. Heat and electricity production
4. People on station (population)
5. External temperatures
6. Wind speeds (wind chill factor)

7. Energy system losses (electrical + thermal)

In some circumstances, critical data may already be being recorded as a routine component of station operations. However, a significantly more detailed evaluation of the system will normally be required, including specifying additional logging points.

11.2 Actions to enable the use of renewable energy resources

Renewable energy resources can play an important role in providing sustainable energy services to operations at Antarctic station.

A wide range of technically-viable energy technologies are available, with proven performance in Antarctica and similar harsh environments. Examples include photovoltaic (PV) solar panels and wind turbines for electricity production, and solar-thermal systems for the production of heat energy that could be applied to warming buildings or melting snow.

The effective and efficient introduction of such technologies into operations, however, cannot be undertaken without first understanding the availability of renewable energy resources and the relationship that these resources have with the station's energy demands.

The 'energy system mapping' project recommended in section 11.1 is therefore also a critical action to enabling the introduction of renewable energy technologies at Antarctic stations. A similar understanding of the renewable energy resources available at the stations, particularly the intermittent wind resources, must also be developed as has been recommended for energy 'use'.

Investigation has determined that only limited and poor quality records of relevant weather data are generally available for Antarctic stations. Some broad assumptions can be made, however, about renewable energy resources. For example, abundant solar energy resources are available during the summer season at all stations, as is to be expected for the geographic region. Wind speed measurements from automatic weather stations (AWS) across the continent can indicate if viable wind resources are likely to be available. However, this needs to be confirmed through further investigation.

Many stations operate existing meteorological facilities which can provide valuable information about the renewable energy resources at the station, particularly wind speeds and directions. Care should be taken to ensure that this data is appropriately collected and stored. It must be noted that the measurement height of a conventional Antarctic weather monitoring station will not be ideal for calculating the potential wind energy resources at a station but will be a valuable resource none the less.

The other key issue that impacts that ability of Antarctic communities to utilise energy technologies is their experience in evaluating, integrating and operating novel equipment and systems. The acquisition of 'hands on' experience with relevant renewable energy technologies is therefore strongly recommended. This is particularly relevant with wind turbine technologies as they are the most likely candidates for all-round use at the station and care must be taken with their operation in Antarctica.

Two approaches are possible to addressing these two challenges of (1) understanding the renewable energy resource potential at Antarctic station and (2) developing operational experience with wind energy technologies.

The more conservative approach would be to initially monitor and evaluate the wind resource at the station, followed by analysis of the potential for wind energy harnessing. An appropriate turbine product could then be selected and installed. However, the lack of practical experience with the technologies would necessitate an interim stage of developing practical experience with a smaller (and cheaper) wind turbine.

The more aggressive and time-efficient approach would be to simultaneously collect wind energy data and develop practical experience with an appropriately-sized and priced turbine. When sufficient data and experience has been compiled, the viability of using wind turbine systems at an Antarctic station can be effectively assessed and an appropriate product procured based on practical knowledge of operations at the station.

Possible turbine products that are small in capacity and therefore relatively low in cost include devices from the suppliers *Windside* (vertical, permanent magnet, upwind design), *Fortis* (horizontal, permanent magnet, upwind design), and *Proven* (horizontal, permanent magnet, downwind design).

All of the wind turbines are developed with low cut-in speeds, high cut-out speeds, and low-maintenance operation The *Windside* turbines are proclaimed to be almost soundless, due to the vertical design, which makes the rotation lower than the wind speed [1]. When it rotates it appear as a solid object and thereby should discourage birds from flying into them. Most likely it would be able to withstand debris in the wind better than horizontal turbines, due to its solid rotating mass. The *Fortis* wind turbines are designed for power ranges from 0.2 – 300 kW and various applications as battery charging, water pumping, grid connection and hybrid systems as wind/diesel and wind/photovoltaic [2]. These are fairly low-priced turbines with many applications around the world. *Proven* wind turbines proclaim to be one of the most robust and reliable wind turbine systems in the world, capable of withstanding severe wind speeds due to their downwind design [3].

The turbine(s) should be installed within the station footprint/boundary. This will reduce the environmental impact and infrastructure demands of the activity and increase the physical connectivity of the project with the station. This is also a favoured initial location for the turbine(s) as the final siting of any larger turbine(s) should be close to the station for a number of reasons. If the in-station location is shown to be less favourable through operational experience and/or future analysis of available wind data, the turbine(s) and future systems could be relocated to more favourable sites in the region.

This activity is recommended as it does not conflict with the recommendation to measure wind resources (as addressed by the upgraded AWS), and additional wind speed measurements could be made from the turbine itself.

Recommendation 2: install 1 or 2 small wind turbines at Antarctic stations over the next available Antarctic summer season, while collecting data about wind resources at the station.

11.2.1 Outcomes from the installation of wind turbines

Proposed outcomes from the installation of turbines include:

1. Gain highly valuable operational experience with the turbines, which will influence future operational and economic considerations such as the purchase of additional and/or larger turbines, the modification of station infrastructure to include wind energy, and the allocation of personnel for maintenance and operation of the energy infrastructure.
2. Highly conservative analysis of the operation of even small wind turbines at Antarctic station indicates that savings in fuel usage can be immediately achieved. This provides an economic and environmental return on investment beyond the practical experience developed through their use.
3. The installation and operation of the turbine(s) would provide a physical expression of a community's interest in energy use and sustainability at the station and serve as a focal point for discussions about the project at the station and within the broader community. This type of 'lighthouse' project is important for generating engagement with, and ultimately support for, the project within the organisation and the broader community.

In addition to these outcomes, further 'value-adding' opportunities will be possible through the installation of small turbines at an Antarctic station.

4. After the 'field testing' at Antarctic, the turbines can be relocated / re-used at other permanent sites where their small generating capacity could be put to more effective use. Summer field camps, for example, could potentially be operated with a significantly high proportion of renewable energy based on input from the relocated turbine(s).
5. Positive experience with the turbine(s) could also be applied to supporting field parties or automated facilities in the region over the summer period.

11.3 Development of a Strategy and Action Plan

The adoption of more sustainable energy practices by Antarctic communities for their operations will be a long-term and complex process. The challenges associated with the process have been examined in detail in the other sections and chapters of the PhD thesis associated with the development of this strategy. The key issues can be summarised as the practical issues associated with understanding energy usage at relatively large facilities (e.g. Antarctic stations), and the need to identify renewable energy resources and develop the experience needed to make sensible choices about new energy technologies.

In addition to these very basic (but important) issues, a wide range of other issues will need to be addressed within the organisation in order to identify and implement changes that are appropriate to the energy needs and 'culture' of the community. These issues range from general knowledge development within the community regarding the need/value of introducing more sustainable energy solutions, to the economic and operational challenges of purchasing and operating energy technologies that may differ significantly from existing systems.

The direction, viability and appropriateness of any efforts to address these issues will be a significantly impacted by the community's ability (as a community, and for the management specifically) to achieve three key outcomes.

Outcome 1: clear identification and specification of a set of common goals relating to the community's use of energy in Antarctica (and perhaps other regions) and the sustainability of the associated energy services.

These goals must be developed through consideration of the current and future needs of the organisation, the goals (or objectives) and culture of the community, its capabilities with regards to adopting new energy technologies, and the technical options that are available to support energy-specific goals.

The development of the goals will be an iterative process, beginning with very broad expressions of intent relating to sustainable operations, and increasing in detail and the setting of targets and methods as experience and knowledge increases within the community.

Outcome 2: understanding and acceptance that any efforts to significantly enhance the sustainability of the energy systems beyond current operations will require a large and long-term effort.

This effort should be expected to include at least 10 years of sustained activity and a commitment to overcome the technical, operational and social challenges associated with introducing new technologies and processes to energy systems in remote and harsh environments.

Outcome 3: development of a strategy to guide and enable the implementation of any technological and operational changes that are required to achieve the energy and sustainability related goals defined for the community's operations in Antarctica.

This strategy could be defined as an 'implementation' or 'change management' strategy for sustainable energy solutions for the community's Antarctic operations.
Achieving these outcomes, including the development of a strategy, will require a change from existing practices. Following a 'business as usual' model will not deliver the required results. The most effective approach recommended to achieve the three key outcomes would be the appointment of an appropriate 'champion' and project manager within the community.

Recommendation 3: Antarctic communities to appoint an appropriate project 'champion' to manage the pursuit and delivery of the 3 key outcomes (goal specification, understanding of long-term nature of the task, and development of an implementation or change management strategy).

11.3.1 Factors for consideration in strategy development

The implementation strategy must be developed with consideration of a wide range of factors, including:

1. The community's goals for supporting operations in a safe, secure and economically and environmentally sustainable manner.
2. The community's current (and future) activities and energy needs in Antarctica.
3. The availability of economic resources available to support the introduction/implementation of new energy technologies, including access to additional or external funding mechanisms and sources.
4. The capability and suitability of new and emerging sustainable energy technologies for use in Antarctic operations.
5. The availability of adequate support and training infrastructure for novel energy technologies and operations.
6. The development and application of appropriate safety/reliability analysis of technologies that have not previously been used in Antarctic operations.
7. The ability of the community to effectively assess its needs and capabilities with respect to these tasks, and its ability to build capacity or access the skills required.

Any implementation strategy must ultimately be developed by the community itself. However, the following framework has been developed to guide the community's activities in the near term.

11.4 A preliminary strategy for Antarctic communities to implement sustainable energy solutions in their operations

11.4.1 Part A: Actions for the very near term (next 3 months):

Action 1: Initiate the collection of renewable energy resource data at the station site(s) as soon as possible (e.g. wind speed and direction measurement at an appropriate height).

Action 2: Initiate (as soon as possible) a project to log the energy generation and usage at the station(s) with a precision that is appropriate for future simulation and evaluation of the station's energy system and operations.

Action 3: Raise the profile of 'energy services' at the station(s) as a subject of significant consideration for the community's management team. Particular effort should be taken to prompt consideration of the need for alternative options to conventional solutions, to take practical actions in the near future, and to develop a strategy to identify, evaluate and then implement appropriate changes. The management team must begin working on achieving the three outcomes presented above before further actions will be of value. Without management awareness and support, efforts to implement more sustainable solutions run the risk of becoming short-term 'boutique' projects that yield little long term gain and can negatively impact future efforts to evaluate and implement sustainable energy solutions.

Action 4: Through the management team, develop broad goals for the community with respect to the use of more sustainable energy solutions in Antarctic operations – as detailed for *Outcome 3* above. The delivery of a detailed briefing to the community management by external experts in remote area energy issues would be an effective mechanism to initiate further activity on this Action.

Recommendation 4: community management receive a detailed briefing by professionals with expertise in the sustainability of remote area power systems.

11.4.2 Part B: Actions for the near term (next 12 months):

Action 5: Raise awareness and understanding of sustainable energy issues in the community through general and targeted education programs; general education activities such as seminars and presentations should raise awareness of issues such as the importance of energy services to operations, energy-linked sustainability, potential changes to the community's energy systems as sustainable solutions are adopted, and the community's goals in relation to pursuing more sustainable solutions; education programs should also be developed for expeditioners about energy usage, and relevant training of specific personnel about energy-related projects such as logging of usage will be needed.

Action 6: Promote 'energy' as a critical factor within station operations
Raise the awareness of energy as a critical component of station operations and the need to optimise energy use and introduce alternative energy sources. Suggested activities include improving understanding of energy usage on station through

detailed technical logging and analysis of the data (see Part 1 of the report), and the inclusion of energy issues in station reporting and management. For example, reporting of energy usage and energy system-related activities by the station leader (SL) to management and external experts who are evaluating the energy system.

Relatively high profile 'lighthouse' projects could also be established on the station to raise the profile of energy as a subject of interest and to practically demonstrate the technologies and concepts involved in pursuing more sustainable energy solutions (e.g. a small wind turbine, as recommended in Section 11.2).

Action 7: Engage relevant partners/stakeholders in discussions about the pursuit of more sustainable energy solutions within the community's operations. Example stakeholders would include relevant government Ministries and commercial suppliers of plant and equipment. Discussions should communicate the community's interests in and potential long-term goals for the adoption of more sustainable practices, identify the potential involvement of partners, and evaluate the interests and capabilities of partners.

Recommendation 5: communities to host a workshop/seminar on sustainable energy use in their Antarctic (and perhaps Arctic) operations with relevant stakeholders in the near 12 months.

Action 8: Engage with the broader Antarctic and international community regarding the use of sustainable energy solutions in the community's Antarctic operations. Other Antarctic operators, and many other energy users around the world, are facing similar issues and questions. Activities such as the International Polar Year (IPY) will provide a range of opportunities to engage with organisations in a similar position and share experiences, approaches, and potential solutions. The IPY program, for example, will include a high profile summit on Arctic energy solutions that will be highly relevant to activities in Antarctica (and the Arctic) and will feature a technology showcase by relevant industry suppliers from around the world. (www.arcticenergysummit.org) Antarctic communities should consider attending events related to this IPY project. Antarctic communities should also consider establishing or joining localised networks that focus on access and implementation of sustainable energy solutions in their area, such as the NordSESIL.net project in the Nordic region [4].

Recommendation 6: attend (or support the participation of an appropriate representative) events tied to the IPY-endorsed Arctic Energy Summit in Alaska in October 2007, and similar activities in the future.

11.4.3 Part C: Actions for the medium term (2-4 years):

Action 9: undertake detailed technical analysis of energy usage at the station(s), including identification of opportunities for reduced energy use through improved management of loads and energy generation infrastructure. Also undertake analysis of the potential for energy generation from renewable energy resources, and the compatibility of these resources with the station operations and load. The collection of adequate data sets will require a minimum of 12 months. Appropriate external expertise should be engaged for this task such as a research institution, and opportunities to utilise research students and additional (research-focused) funding sources should be pursued as a means of reducing the cost to the community for such actions.

Action 10: Evaluate experiences learned from practical projects (e.g. small wind turbines) regarding the use of renewable energy technologies in Antarctic operations. Issues to consider include the performance of the technologies in polar environments, their integration with station infrastructure and operations, and training and infrastructure/support requirements for the technologies.

Action 11: Develop (within 2 years) preliminary organisation/community goals with respect to the 'sustainability' of the community's energy services for their Antarctic operations. These goals should provide an indication of long-term intent and be sufficient to guide further actions relating to the investigation and selection of energy supply infrastructure for the Antarctic station – particularly the testing and acquisition of renewable energy technologies.

Action 12: Review (after each 2-year period) the community's 'energy sustainability' goals based on increased understanding of the practical viability of technologies, the changing needs of operations, and the 'attitude' of the community. For the reviewed goals, develop more comprehensive guidelines for activities including milestones (calendar dates) and objectives.

Examples of potential objectives for the installation of renewable energy generating capacity at the station include: to a level of a) X kW peak capacity; b) X kWh/year output; c) X% of installed generating capacity; d) capacity to replace X tonnes CO_2 emissions/year; e) to a capital value of X Million \$; or f) to enable a delivered energy cost of X \$/kWh using conventional and renewable energy resources. The objectives and milestones should be conservative but make a meaningful contribution towards achieving the broad goals of the community with respect to pursuing sustainable solutions.

11.4.4 Part D: Actions for the long term (5-10 years):

If they are applicable to the goals defined by the community in the previous actions, the following actions should be considered during the 5-10 year time period (for example, if the community specifies a goal of increased use of renewable energy resources at the station and or in general operation):

Action 13: Install larger generating capacity from wind turbines and associated renewable energy infrastructure to meet a more significant component of the existing station loads (e.g. a 30-kW or larger turbine with renewable energy storage technology). Lessons from other Antarctic operators who are also investigating the use of renewable energy resources, such as the new Belgian station [5], will be relevant in this regard.

Action 14: Evaluate and subsequently integrate other renewable energy technologies into the station's operations as appropriate for the energy demands, renewable energy resources, and availability of viable technologies. Example applications would include solar thermal heating systems for space heating and hot water production and photovoltaic solar systems for electricity generation. The merits of installing such technologies could be effectively assessed through detailed computer simulation of the station's energy systems.

Action 15: Work with relevant partners to enable the effective and efficient inclusion of appropriate renewable energy technologies into any further expansion of the station's energy systems.

Action 16: Assess the merit and technical and operational viability of utilising renewable energy technologies in other elements of the community's operations, such as remote and semi-permanent field camps, summer field camps, automated facilities, and satellite components of Antarctic station.

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Chapter 12. Conclusions & Further Work

This research project aimed to address current limitations in the area of effective integration of energy technologies (particularly novel sustainable energy solutions) into communities by studying the interactions between technologies and communities. The study focused on the interface between systems using renewable and hydrogen energy technologies and the communities of scientists working in the remote, harsh and pristine Antarctic environment. The research project was multi-disciplinary in approach, and included components of technical (engineering) analysis and investigation of the influential social issues relating to the interaction of energy users with such technologies. The primary research objective was the development of tailored strategies and recommendations to help the Australian Antarctic research community identify and access appropriate and sustainable energy solutions. The research also aimed to study and comment on how efforts to enable improved access to sustainable energy solutions for Antarctic communities could be utilised by communities in other parts of the world to address the global need for improved access to such solutions.

These aims and objectives were successfully achieved through the definition and execution of three primary tasks:

1. A comprehensive evaluation of the roles that hydrogen energy technologies could play in the operations of the Australian Antarctic community, specifically when coupled with renewable energy technologies.
2. A detailed engineering analysis of the technical viability of using hydrogen technologies for large applications in partnership with renewable energy technologies. The analysis achieved its additional aim of using as many 'real world' constraints and data sets as possible and has subsequently provided the Australian Antarctic community with highly relevant information to guide their future ambitions with their permanent research stations; particularly the station (Mawson) that was the focus of the engineering analysis station.
3. Comprehensive and multi-faceted engagement with the Australian Antarctic community that led to the identification and improved understanding of the non-technical issues associated with the evaluation and implementation of hydrogen technologies, and enabled the assessment of the appropriateness of hydrogen technologies for the community.

The following conclusions and recommendations for further work can be drawn from the research results.

12.1 Conclusions

Conclusion 1. Hydrogen energy technologies are technically viable at the current time for use in a number of Antarctic applications. The diversity in size, capability and intended applications of the many different technologies that are close to market release also greatly increases the practical viability of hydrogen technologies in the near future for a wider range of Antarctic applications.

This study has confirmed and explored further the hypothesis of previous studies that hydrogen energy technologies can play valid practical roles in Antarctic operations, and subsequently examined what actions need to be taken to overcome technical and social barriers to further evaluation and implementation. Chapter 7 closely examined applications for current and emerging hydrogen energy technologies in a range of common Antarctic operations, including permanent stations, field camps, transportation demands, and energy use in mobile devices. The results conclude that there are many valid and varied technical roles in all such applications, and identify possible short- and long-term routes for introduction of the technologies. The technical analysis presented in Chapter 8 also examined in detail, via energy system simulations, the utilisation of hydrogen technologies for the largest energy user on the continent – permanent stations – based on the operation of Mawson station and the currently installed wind turbines.

Conclusion 2. There are limitations in the currently available components of hydrogen energy systems, ranging from price to lifetime to performance in cold climates, that restrict their use in a number of Antarctic applications. There are also limitations in the capability and versatility of the tools and resources available for design and evaluation of hydrogen energy systems. However, from an overall perspective, none of these factors is a significant detriment to the use of hydrogen technologies at the present time.

Conclusion 3. Social issues are the biggest barrier to the implementation of novel energy technologies such as hydrogen into the Australian Antarctic community – the current lack of community will and limited capability to identify, evaluate and implement solutions are significant impediments to any efforts to evaluate and introduce energy supply alternatives. Social issues also appear to be the largest barrier to the growth of sustainable energy technology markets on a broader scale.

Conclusion 4. Local environmental issues are not as significant as anticipated as drivers for changes to Antarctic energy systems and the evaluation and introduction of cleaner energy solutions. The protection of the local Antarctic environment and ecosystems from fossil fuel-related pollutants was expected to provide a compelling motivation to adopt cleaner energy solutions and thereby provide a mechanism to overcome the dominant social barriers that exist in other communities. However, the research has shown that the Australian Antarctic community generally views the current state of play with regards to significant fossil fuel use as acceptable from an environmental perspective. Economic factors, in contrast to local environmental issues, are emerging (perhaps in proportion to consistently rising fuel costs) as a far more compelling motivation to consider any alternatives to fossil fuels. Renewable energy resources, on the basis of their localised availability (therefore minimal transport requirement) rather than environmental performance, may therefore receive greater attention and support in the future if fuel prices continue to rise.

Conclusion 5. The use of hydrogen energy technologies in small-scale applications is expected to be the largest and most viable market for hydrogen technologies in Antarctic applications in the near-term. Such applications are also the easiest to address with respect to the current capabilities in the community and have the lowest economic cost to achieve significant levels of penetration. In addition, small-scale applications for hydrogen technologies offer the greatest potential for transfer of technologies and skills to and from other similar-sized applications around the world. On a global scale, small-scale applications of hydrogen technologies are also expected to be the largest and most viable early market and so are the focus of many commercialisation efforts for emerging products.

Conclusion 6. For large-scale applications, it is recommended that efforts to introduce renewable energy generation and storage systems do not focus on achieving 100% independence from fossil fuel supplies. Practical, safety and economic considerations support the continued availability and use of fossil fuel-based energy systems in the short and medium term. Ambitious targets such as 90% independence from fossil fuels have been shown to still enable significant changes in environmental and economic performance without the much greater costs and operational risks of fully independent systems. This approach is also highly transferable to many small-scale applications but achieving 100% energy independence is also more viable for such applications.

Conclusion 7. Antarctic communities are more likely to benefit from the activities of others in the evaluation and implementation of hydrogen energy technologies than to be leaders in the development of early markets, even though certain characteristics do make them attractive as early adopter markets. This analysis is based on the lack of cultural drive with Antarctic communities to serve a role as early adopters, and the more attractive qualities of markets such as the Arctic region to serve as early adopters. A project proposal specifically focusing on sustainable energy technology capacity building in the Nordic region of the Arctic was subsequently developed based on this argument, successfully funded, and has now commenced operation (www.NordSESIL.net). The true viability of transferring technologies and solutions from early adopters in the Arctic region to larger but less capable markets, such as the approximately two billion people in the developing world who do not have access to modern energy services, remains to be determined.

Conclusion 8. The high level of technical and social/cultural changes required within communities to facilitate a transfer away from fossil fuel-based energy economies will require carefully developed strategies. Such strategies will ensure (or at least improve the chances) that proposed solutions are appropriate for the needs of the community and within their current and future capabilities. Strategies should consider specific energy goals, existing circumstances, and also identify peripheral issues that will influence the introduction of novel energy technologies (i.e. developing training of maintenance personnel, or evaluating suitable conditions to retire existing infrastructure etc.). A lack of focus is evident for the current energy strategy of the Australian Antarctic community, as illustrated by the return of one (of three) wind turbines from Mawson station and the stalled Hydrogen Demonstration

Project at Mawson station. This suggests that a detailed strategy for future energy services is needed. Strategy recommendations to enable change in Antarctic communities (if motivated) has been developed and tested via successful application to another national Antarctic research program. This framework for creating such strategies is transferable to other cold region communities or other communities around the world on a more general basis.

Six recommendations were devised during development of the strategic framework that apply to communities in Antarctic and other regions who are seeking to identify and implement more sustainable energy solutions:
Recommendation 1: develop a specific project for 'energy system monitoring' at Antarctic stations as quickly as possible (or review existing monitoring programs).
Recommendation 2: install 1 or 2 small wind turbines at Antarctic stations over the next available Antarctic summer season, while collecting data about wind resources at the station.
Recommendation 3: Antarctic communities to appoint an appropriate project 'champion' to manage the pursuit and delivery of the 3 key outcomes (goal specification, understanding of long-term nature of the task, and development of an implementation or change management strategy).
Recommendation 4: community management receive a detailed briefing by professionals with expertise in the sustainability of remote area power systems.
Recommendation 5: communities to host a workshop/seminar on sustainable energy use in their Antarctic (and perhaps Arctic) operations with relevant stakeholders in the near 12 months.
Recommendation 6: attend (or support the participation of an appropriate representative) events tied to the IPY-endorsed Arctic Energy Summit in Alaska in October 2007, and similar activities in the future.

12.2 Further Work

A number of areas where further work is required can be drawn from the outcomes of this research project.

Work area 1. The core technology components that enable the use of hydrogen as an energy carrier still require further development, such as to improve the lifespan of fuel cell stacks or to reduce the economic cost of all components. Such improvements will significantly improve the technical and economic viability of using hydrogen technologies in a wide range of Antarctic operations. Chapter 8, for example, demonstrated that improvements in the operating efficiency of conventional electrolysers when in idle mode (not producing hydrogen) could have a major impact on the size and cost of all other elements of a wind-hydrogen energy system.

Work area 2. The computer simulations of the wind-hydrogen system at Mawson station presented in Chapter 8 utilised the currently available modelling resources for such applications. Limitations in the modelling tools, however, required a number of compromises and idealistic assumptions to be adopted to facilitate modelling of the actual energy system design at Mawson station. The inability of the wind-hydrogen system models, for example to integrate combined heat and power (CHP) features, was a key area of deficiency. Further work is therefore required on the development of fully flexible modelling tools for wind-hydrogen energy systems, particularly for applications in cold regions where thermal energy demands are a significant component of the total energy system operation.

Work area 3. Although a strategy framework and specific recommendations has been developed for use by the Australian Antarctic community, and other such communities, the framework is yet to be applied by the community. Work remains in engaging with the community for collaborative (or self-motivated) development of energy strategies based on the proposed framework.

Work area 4. The concept has been proposed in this thesis that technologies, skills, methodologies and experiences developed during the evaluation and integration of novel energy technologies such as hydrogen into early markets in the Arctic should be transferable to communities in other parts of the world. Potential participants (as recipients) in the transfer could include remote communities in the developed world (e.g. outback Australian farms), niche high value and high performance markets such as the military or eco-tourism, and international aid and development efforts that seek to improve energy access for billions of people in the developing world. Whilst showing promise, this concept is yet to be tested.

Work area 5. A practical outcome from this research thesis is the initiation of the Mawson Hydrogen Demonstration Project – a project that has experienced a complicated history, and at the time of writing is approaching collapse due to social challenges. This project, even if the initial goal of demonstrating a small-scale wind-hydrogen system for a remote science facility is not achieved, can provide many valuable lessons for future proponents of hydrogen energy projects in Antarctica and elsewhere. The project itself should be evaluated to determine what happened with the project (and why the project stagnated), what lessons can be learnt from the experience (positive and negative impacts) from a technological and social perspective, and what could or should happen next with the project and the broader theme of evaluating hydrogen energy use in the Australian Antarctic program.

One suggested approach to build on the outcomes from the Mawson Hydrogen Demonstration Project is to integrate the 2-kW fuel cell component into a new collaborative venture with a Nordic partner to demonstrate a similar wind-hydrogen energy system in a northern hemisphere context. The existing project will be completed in early 2008, and there are no specific plans for 'retirement' of the infrastructure and equipment. The fuel cell, specifically designed for operation in low temperature environments and provided by a small Swedish firm, will have had negligible use and is therefore capable of making a viable contribution to further research efforts. Colleagues at the Institute for Energy Technology (IFE) in Norway who have provided extensive support with components of this thesis, including co-supervision, have previously expressed enthusiasm to develop a practical demonstration and development project for a wind-hydrogen system in the Arctic. Identifying and funding a suitable fuel cell component was one of the main impediments to establishing the project. An Australian contribution of a suitable (and already funded) component would make such a project far more feasible. A number of issues at the time of writing could also provide a positive window of opportunity for this suggestion – the election of a new Australian government with a strong basis on climate change issues, the commencement of the International Polar Year (2007-

2009), and the scheduling of the next World Hydrogen Energy Congress (WHEC) in Brisbane, Australia in mid-2008.

To that effect, the election of a new Australian government and a new minister for the environment portfolio will naturally lead to a desire for the new actors to distance themselves from initiatives - particularly those with limited success - of the previous administration. In addition, a decision will need to be made at some point as to the future of fuel cell and other components when they are decommissioned and removed from Antarctica. An offer to take custody of the fuel cell could be well received by a new minister as it would be a chance to responsibly retire the project and equipment and to turn a previously poor performing project into a positive initiative for the new government.

The Australian Antarctic Division could also be expected to be happy to identify an efficient path for disposal of the fuel cell, particularly if it can lead to a positive outcome and generate an image of generosity in passing on such a valuable component for others to also learn from. Such an exchange of technology and knowledge from Antarctica to the northern polar climates would also fit very well with the current international polar year initiatives.

The WHEC conference in July 2008 would be a well timed and suitably themed forum to announce and define a new collaborative north/south cold climate demonstration of innovative sustainable energy solutions for isolated communities.

Work area 6. In addition to further work on the above elements of hydrogen energy use in Antarctic operations as a means to enable more sustainable energy services, further work should also be undertaken on identifying and evaluating other areas of energy supply for Antarctic communities. Questions that should be addressed include identification of other methods of reducing energy demand, providing primary energy sources, and storing energy for stationary and transport applications.

Work area 7. More detailed technical and economic analyses to identify optimal hydrogen energy system solutions are suggested. Such work could also include laying the grounds for basic system design (e.g. sensitivity analysis, loss of power probability, considering the variability of weather over different years, etc).

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Appendices

The following appendices have been developed to present additional and supporting information that was not appropriate for inclusion in the body of the thesis.

Appendix 1: Planning Institute of Australia conference paper, 2004, *Hydrogen – Fuelling the Future of Tasmania*
(9 pages)

Appendix 2: Additional information on the computer simulation of a wind-hydrogen system for Mawson station
(34 pages)

Appendix 3: Further analysis of wind speed data from Mawson station
(8 pages)

Appendix 4: A worksheet for undertaking HYDROGEMS modelling work
(2 pages)

Appendix 5: Application for research to the Human Research Ethics Committee (Tasmania) Network for the project "*Interviews to identify current attitudes towards hydrogen energy use in Antarctica and other regions of Australia*"
(8 pages)

Appendix 6: Human Research Project Information Sheet
(3 pages)

Appendix 7: Human Research Project Interview Questions
(3 pages)

Appendix 8: Details of community engagement activities
(6 pages)

Appendix 9: International collaborative project proposal: Sustainable energy systems for polar communities via renewable hydrogen energy technologies
(2 pages)

Presented at the Planning Institute of Australia annual conference, Hobart, Tasmania, 26th February, 2004

Hydrogen – Fuelling the Future of Tasmania

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David Pointing is a PhD candidate at the University of Tasmania, investigating the use of renewable hydrogen energy technologies to support Australia's Antarctic research activities. This paper presents an overview of the concept of the 'hydrogen energy economy', focusing on the use of hydrogen as a fuel in the transport sector. The key hydrogen energy technologies will be reviewed, and examples presented of their recent use in demonstration and pre-commercial vehicles and energy supply systems. The paper concludes with a brief analysis of how Tasmania could benefit from involvement in the global hydrogen economy, and a summary of current research and development efforts in the State.

Appendix 2. Additional information on the computer simulation of a wind-hydrogen system for Mawson station

This appendix provides additional information about the computer modelling activities presented in Chapter 8. Issues addressed in further detail include:
1. Process for the model development
2. Preparation of the input data
3. Process for undertaking the energy system modelling (simulations)
4. Example of the analysis technique for the modelling results

2.1 Detailed analysis of model development

The development of the computer models used to simulate the energy system at Mawson station was completed through two steps. The actions undertaken in each of these steps are reviewed in the following pages.

2.1.1 Selection of modelling strategy and energy system designs

The initial step in the development of the modelling tools was the selection of a general strategy with which to approach the modelling process and the identification of a potential energy system designs. This selection process included discussions with the user community and experts in hydrogen energy system simulation. Factors considered in the selection included the practicality of conventional energy system designs relative to the more innovative concepts presents in Chapter 4; the modelling capability of the author; the availability of existing modelling resources and comparable projects; the time resources available in the research; and the outcomes sought in conducting an initial assessment of the use of hydrogen at Mawson station.

A broad strategy was subsequently developed that used simple designs of hydrogen energy storage systems which integrated into the existing centralised energy supply infrastructure of Mawson station. In these systems, the hydrogen energy sub-system would duplicate the role of the conventional centralised power system that is based on use of stored diesel and diesel electric generators (DEGS) to meet electric loads not met by the wind turbines. However, the hydrogen sub-systems included the additional feature of utilising excess wind energy to generate hydrogen for storage rather than requiring the importation of fuel.

An important simplification was also made to simulate the current process of meeting the station's heating load with a combined heat and power (CHP) system that captures waste heat off the DEGS for distribution through a hydronic heating system. For the wind-hydrogen systems considered in the simulations, the analysis focused on the time critical electric loads or converted the heating loads to electric loads and applied them at expected periods of high wind power generation. This approach was also required due to the limitations at the time of modelling resources in their ability to effectively model wind-hydrogen systems with CHP heating loads.

Three configurations of wind-hydrogen energy systems were selected:

System 1: wind-H2 system with FC only,
System 2: wind-H2-diesel system with FC and DEGS
System 3: wind-H2 system with HEGS and FC

This approach of using centralised hydrogen technologies to effectively replace existing infrastructure was selected over more innovative system designs that utilise the potential capabilities of hydrogen technologies due to limitations in existing modelling resources and the complexity of the control strategies that would be required to accurately control all the system components. The simplified approach was also seen as efficiently enabling assessment of the basic viability of utilising hydrogen energy resources at Mawson. Successfully proving that the energy demands and availability of primary energy resources (wind) for the station could be balanced with sensibly sized hydrogen energy components was seen a sensible first step before investing significantly greater effort and time in simulating a complex wind-hydrogen energy system with CHP capabilities.

2.1.2 Selection/construction of the modelling tool

The second action in developing the computer models was to select and/or construct a modelling tool. The characteristics of modelling tools that were rated as important included: high resolution simulation of energy and mass flows; modelling algorithms that were appropriate for the application (wind-H2 systems); focus of results on the viable performance of energy systems; a respected pedigree with proven field performance of models developed for other projects; suitable for rapid adoption by a non-expert user (as this is not a modelling-focused PhD); and potential for later operation by user communities as a component of their independent assessment of energy system options.

After some consideration of the available resources and options, the decision was made to utilise the proven modelling capabilities of the TRNSYS 15 (Transient Simulator) modelling software, with the integration of specially developed component models for hydrogen technologies (the HYDROGEMS library). An external research supervisor with leading expertise in hydrogen system modelling (Dr Øystein Ulleberg, developer of HYDROGEMS) was identified to provide guidance in this process. The principal alternatives included the development of a new set of hydrogen energy component and system models (working in a range of possible software programs), or to utilise one of the freely available modelling tools that can be sourced from government energy agencies around the world. Examples of such tools include RETSCREEN, Homer and Vipor.

This research project fortuitously coincided with the maturation of the HYDROGEMS library and the packaging by Ulleberg of modelling resources, user interfaces and result analysis tools into a convenient 'toolbox'. Developed for use with a commercial project that had many similar characteristics to the project proposed for Mawson station, the "Wind-Hydrogen Energy System Simulator" was well suited as a modelling tool for this research.

The details of the development of this modelling tool, including the specification of contributions by the author, and motivations for its selection are detailed in the following three steps:

Step 1: Model construction for energy system 'projects'
Project models of energy systems are assembled in a graphical environment using individual models for each of the components of an energy system. Each high resolution modular model includes the variables and parameters (potentially many) that influence the operation of that component. The component models required for the Mawson wind-hydrogen system include the obvious physical components of the system (WECS, FC, DEGS etc) and components for data input (wind, load), output (results) and algorithms to control the interaction of the system components during operation (control strategy). This assembly is undertaken using TRNYSYS 15 software, using generic models for most components and specific HYDROGEMS models for the hydrogen components.

Individual TRNSYS projects were developed by Ulleberg for each of the three systems considered in this research. These projects could be executed directly within the TRNSYS environment, and this function was used during their development for quality assessment. However, the TRNSYS environment is not well suited to the efficient optimisation of system designs due to the labour-intensive process of changing component and system parameters and evaluating the results. A more effective approach to executing the models is provided through a TRNSED (TRNSYS Edit) interface.

Step 2: Development of an Energy System interface for system optimisation
The TRNSYS 15 program includes a function that enables a project to be packaged into a self-executing model interface that eliminates the need for users to enter the primary TRNSYS working environment. This TRNSYS Edit (TRNSED) environment provides a convenient graphic interface where the user specifies inputs for a reduced number of component variables from pull-down menus or by entering numeric values. The details and appearance of the TRNSED interface are influenced by text coding (similar to HTML language) and through settings specified in the original TRNSYS project - variables and parameters for every component can be 'locked' within the TRNSYS environment, and the unlocked elements appear as variables in the TRNSED interface.

Ulleberg developed TRNSED interfaces for the three systems considered in this research. Some modification to these interfaces was undertaken by the author to enable the integration of data relating to Mawson station (wind speeds, energy demands and wind turbine data), but no modifications were made to the original TRNSYS project files.

The TRNSED 'energy system interface' provided a more efficient method of executing multiple simulations with minor modifications to key component parameters and variables when compared to the TRNSYS environment. However, the results from the simulations are the same format as that provided by the TRNSYS working environment, namely low quality graphs of key results and large data files. The graphical method is appropriate for the rapid primary assessment of system designs, such as through the evaluation of the H2 storage state of charge, but the data tables are poorly suited for further analysis of the designs. These constraints prompted Ulleberg to develop a more efficient and "user friendly" interface for utilising modelling projects developed in TRNSYS.

The TRNSED interface for System 1, including modifications for the Mawson energy system, is illustrated in Figure X.X (bottom) following.

Step 3: Development of a primary toolbox interface
A graphical interface to enable the efficient selection and execution of simulations of various energy system designs and the subsequent analysis of results from the simulations was developed by Ulleberg in 2004. This 'toolbox interface' was constructed using the product EES (Engineering Equation Solver). EES enables developers to create functional graphics environments to display the various components of a modelling project (e.g. three different system designs), to execute links to external programs (such as the TRNSED file for each project) and to present results from simulations in numeric and graphical formats. EES is also well suited for other forms of simulation and post-processing of results. EES also provides a convenient functionality whereby all related files and executable programs can be bundled into an independent and executable product suitable for distribution to other users who do not have access to the core software packages.

Early in 2004, Ulleberg developed a specific toolbox for a wind-hydrogen system as part of an IFE commercial project. The toolbox was subsequently used to identify an optimum system design for a specific project that was then realised by the commercial partners. The later commissioning of the physical infrastructure provided a unique opportunity to verify and improve the performance of the TRNSYS model used in the project (System 3).

The modelling toolbox is currently commercially sensitive; however, the author's relationship with Ulleberg through this research provided an appropriate forum to share the toolbox for academic application to a project with similar design requirements to those of the initial commercial project.

The attributes of efficient and easy functionality for executing and analysing energy system models, the portability of a packaged 'toolbox', the foundation of high resolution modelling, and the proven and improved performance of the models all prompted the selection of Ulleberg's "Wind-Hydrogen Energy System Simulator". The EES graphical interface for the toolbox, with some minor graphical modifications to indicate the Antarctic application, is illustrated in Figure X.X (top) following. The primary limitation of using the pre-existing toolbox was a limited capability to modify elements within the primary model, such as the control systems or energy technology components. As the characteristics of the Mawson station energy system were seen to be very similar to the original project that the model was developed for, this limitation was not seen as a great concern.

In terms of the author's contribution to the TRNSYS model development, a number of months were spent developing projects in the TRNSYS environment during the initial assessment of modelling tools. This activity enhanced the authors understanding of the processes, architecture, and limitations of the modelling package. However, access to the powerful simulation capabilities of the TRNSYS software was restricted by the modelling process that was inherently complex, difficult to master, and time consuming for a novice to computer modelling. Discussions with Ulleberg indicated that it would take considerable time to build the expertise and experience necessary to design and construct useful models of wind-hydrogen systems for Mawson station. The timely development of a distributable modelling toolbox by Ulleberg with appropriate characteristics for modelling Mawson station provided a valuable opportunity to utilise models that had been developed by an expert and field tested and refined. The application of the modelling tools was also anticipated to provide a worthwhile assessment of the potential to apply the models to other projects.

The author also spent time working in the TRNSED and EES software environments. The experience with TRNSED provided an important understanding of the links between the interface and the TRNSYS models and was applied in modifying specific files to enable the application of Ulleberg's original toolbox to the unique circumstances of Mawson station. Experience in the EES environment included developing alternative models and understanding the architecture and operations of the existing toolbox interface, although no modifications to this interface were required (except for graphical variations).

Antarctic WIND/HYDROGEN ENERGY SYSTEM SIMULATOR

Simulation Summary

IFE 2004-12-01 UTAS

System 1	System 1 ??	is selected
System 2	System 2	
System 3	System 3	

Energy Balance

		MWh/year	%
INPUT	WECS	4721	86
	DEGS or HEGS	0	0
	Fuel Cell(1)	732	13
	Deficit (import)	7	0
	SUM input	5459	100
OUTPUT	User Load	1307	24
	Electrolyzer(2)	2518	46
	Excess (export)	1634	30
	SUM output(3)	5459	100

Comments

(1) Power from FC-inverter

(2) Power to ELY-inverter

(3) Relative difference (input-output)/input

-0.00 [%]

Initialize	Initialize Program
Upload	Upload TRNSYS data into EES
View Plots	View Plots
Monthly Value	More info
Performance	System Performance Indicators
Economize	Economic Calculations
Statistics	Operating hours statistics
Checks	Simulation Checks

Mass Balance

Hydrogen		Nm^3/year	%
INPUT	Electrolyzer	505636	100
	SUM Input	505636	100
OUTPUT	Fuel Cell	510271	100
	HEGS	0	0
	Dumped H_2	0	0
	SUM Output(1)	510271	100
Diesel		L/year	
INPUT	DEGS	0	435668 (reference system)

Comments

1 Relative difference (input-output)/input

-0.92 [%]

Antarctic

WIND/HYDROGEN ENERGY SYSTEM SIMULATOR

System 1 = WECS + H2-system

Simulation Input

Location (wind and load data is automatically uploaded)	Mawson ANT (eleconly)	
Peak load	200	kW

WECS - Wind Energy Conversion System

Type of WECS	Enercon E30 Polar rated (300 kW 34 m)	
Number of identical wind turbines	3	-

Hydrogen System

Electrolyzer		
Rated Electrolyzer Power	310	kW
Minimum electrolyzer idling power	40	%
Electrolyzer OFF-switching set point	99	%
Electrolyzer ON-switching set point	80	%
Fuel Cell		
Rated Fuel Cell Power	570	kW
Minimum fuel cell idling power	5	%
Fuel Cell OFF-switching set point	20	%
Fuel Cell ON-switching set point	10	%
H2-storage		
Maximum allowable H2-storage pressure	200	bar
Physical volume of H2-storage	365	m^3
Initial H2-storage state of charge (SOC)	55	%

Note! OFF-switching of electrolyzer and fuel cell = switching into idling mode

Figure X.X: Primary toolbox interface (top) and energy system interface (bottom).

2.2 Detailed analysis of input data preparation

In addition to the selection of a modelling strategy and the subsequent identification of a specific modelling tool, the sourcing and preparation of relevant data sets for input to the model was an important element of the simulation process. The types of formats of the data sets were influenced by the energy system designs that were to be simulated and the architecture of the modelling tools. The raw data relevant for Mawson station was sourced from the user community (Australian Antarctic Division) and the necessary modifications and analysis to generate relevant input files was completed the author. Considerable time and effort was invested in developing accurate data sets as the quality of the input data was seen as a key factor in influencing the relevance of the output data files.

The following pages detail the processes and results for the generation of data files for the key inputs to the wind-hydrogen simulator, including:
1. the electrical and heating loads
2. wind speed data

2.2.1 Generation of electrical and heating load data

The magnitude and time of occurrence of the energy loads that an energy system must meet are key inputs to any energy system simulation. The 'Antarctic Wind/Hydrogen Energy System simulator' requires this information in the form of a single data set (location file) that includes an annual normalised (0.0 to 1.0) load profile with an hourly time step. The user enters a maximum load for the energy demand into the simulator, enabling assessment of a range of station loads without modification to the location file.

For many energy simulation projects, the various energy demands within the project can be integrated into a single load profile based on the assumption that electrical energy demands dominate any other loads. However, as Mawson station operates in a harsh polar environment, it has two key categories of energy demand that are comparable in magnitude: the heating load and the electrical energy load. Both of these load varied over the hours of a day (daily profile) and the months of the year (monthly profiles) due to the changing activities of the station population (indoor, outdoor, working, recreation), the changing size of the population (summer and winter) and the variations in external conditions (temperature, wind chill, light levels).

The electrical load covers all direct electrical energy consumption related to the station's operations, including domestic and recreational activities (lighting, devices and appliances) and the functional activities of a research facility (research equipment, computers, communications, lighting, laboratories, workshops, waste treatment etc). The electrical demands have a critical dependency on constant service availability where any disruption to supply results in brown-outs, black-outs and/or failure of operations.

The heating load covers all of the thermal energy demands on the station and has a much lower dependency on constant service availability; the thermal energy demands primarily include space heating for buildings (serviced via the CHP hydronic heating network) and the production of water via the melting of ice. Each of these processes has an inherent capability for energy storage due to the ability for thermal storage within the hydronic heating system and the ability to store water. This potential for energy storage enables the thermal energy demands of the station to be manipulated for better management of the total station load.

In an ideal situation, simulation of Mawson's energy systems would be undertaken with a modelling tool that utilises the dual energy demand profiles (electrical and thermal) and the CHP design of the existing energy system. Unfortunately, simulation tools with such capabilities that were also appropriate for use with hydrogen energy technologies were not available. This is illustrated by the 'Antarctic Wind/Hydrogen Energy System simulator' use of a single load profile and lack of CHP capability, even though it is a highly refined and proven modelling tool for hydrogen energy technologies that represented the state of the art of such tools at the time. The author is aware of efforts external to this project that are currently underway to develop an improved simulation tool that includes CHP capabilities and portioning of the electrical and heating demands for energy systems.

For this project, the limitations of the modelling resources were overcome to adequately represent the true energy demands of Mawson station via two approaches to creating a single energy demand profile. These approaches are examined in further detail in the following pages, and include:

1. *Conservative approach* – heating loads were 'forced' to occur each day at times of anticipated excess wind energy and integrated with the existing electrical demands into a single load profile.
2. *Practical approach* – the detailed simulation process only considered the highly time critical electrical loads, and the capability of the energy system to meet the station's heating loads was assessed using post-simulation data.

Conservative approach **to load profile creation**

This approach sought to create a method of simulating the complete Mawson system (separate heating and electrical loads and their different time dependencies) while working within the constraints of the chosen modelling tool (single load profile and no CHP capability). As a hydrogen system would provide realistic opportunities for CHP thermal energy generation that would not be captured in the model, it was seen as important to minimise the direct use of the hydrogen system for heat production, while ensuring that full heating needs were included in the assessment. Failure to do so would result in inefficient and inaccurate use of the hydrogen system. Minimal direct use of hydrogen for heating was achieved by making the calculated assumption that the heat energy could generally be sourced directly from the turbines.

The largest potential constraint for this approach was predicted to be an over-sizing of the hydrogen system in the model as the heating needs of the station would not all would be met directly by the wind and some hydrogen fuel would be used directly to meet heating load. Such behaviour departed from what would happen in practice as thermal energy would be captured off any use of the hydrogen system, and if the hydrogen system were used directly for heating it would be twice as efficient as calculated by the model due to the CHP capability.
This approach therefore provides a conservative estimate of energy system needs, but additional factors such as impact of wind-chill factor on station loads have not been quantified.

The load profile for the conservative approach was developed through the creation of daily load profiles for the heating and electrical loads, monthly weighting factors for the two load categories, and the integration of these factors into a single load profile.

Step 1 - Daily heating and electrical load profiles:
Heating and electrical load data at five minute time steps was provided by the AAD for Mawson station for an individual day (29th October, 1999) [1]. This data related to the operation of the station as a diesel-only CHP system, and did not incorporate modifications to the station design and strategies for meeting the thermal energy demand that occurred with the installation of the wind turbines in 2003. In this previous system, waste heat was captured off the generators at all times with deficits in heat load met using diesel-fed boilers - this was very much a heating energy supply rather than demand driven system. The integration of variable speeds pumps on the hydronic system reduced the need for boiler operation (*REF*) and the turbines provided an alternate and more intermittent source of primary energy that utilised the thermal storage capabilities of the hydronic system more than the previous design.

The detailed 1999 data was compared to less detailed data for recent years and indicated that the total annual heating and electrical demand figures were comparable to each other but differed slightly in magnitude to more recent annual figures. However, it was determined (in consultation with the AAD) that the separate heating and electrical time/load profiles for the day in question could be assumed to represent the daily profiles for current operations. The data was subsequently used to generate daily load profiles for each load category, with hourly load values normalized over the day period.

Anecdotal evidence from AAD personnel who had spent numerous years at the site indicated that the wind patterns were characterised by higher winds in the evening and early morning (9pm - 8am) and lower winds during the daytime. Wind speeds were also generally higher during the winter months, coincident with higher thermal energy demands (colder external temperatures and wind chill). This provided an opportunity to further apply the energy storage capability of the hydronic heating system as a means of excess wind energy storage and to manipulate the times of thermal energy demand to better match the wind resource. Extensive analysis of the wind data set used in the simulation (based on 2003 data) confirmed that peaks in the wind speed occurred during the evening (10pm-3am) on 265 days of the year (72%). Peaks were identified as wind speeds within 30% of the maximum wind speed measured over a 24 hour period. This analysis confirmed the anecdotal evidence and provided a foundation for developing a load profile that 'forced' the heating demand to occur at times best suited to excess wind power production.

The normalized heating loads for the conservative approach were consequently manually 'forced' to occur during anticipated periods of higher winds in the evenings (10pm - 9am), in addition to the existing thermal loads during those periods . As an entire day of heating load had to be met in half the time, the resulting normalised hourly heating loads during the evening were twice as high as would really occur - the load profile was therefore 'quasi' normalized.

These actions produced 'normalised' daily profiles for the heating and electrical loads. Their combination resulted in a total hourly station load that was approximately 50% greater during the evenings than witnessed in reality due to the 100% electrical load and 200% heating load occurring at the same time.

These actions also enabled the identification of the maximum station load, projected at 400 kW.

[1] file reference: "Mawson station (staion) load"

Details of the daily electrical and heating (forced and unforced) load profiles ('normalised') are provided in Table X.X below. The daily profiles of electrical and forced heating loads are also represented visually below in Figure X.X.

Daily energy load profile

time (hour)	elec load	heat load *forced*	heat load *unforced*
1	0.90	1.62	0.74
2	0.91	1.47	0.67
3	0.88	1.61	0.73
4	0.90	1.52	0.69
5	0.87	1.61	0.73
6	0.88	1.69	0.77
7	0.92	1.49	0.68
8	0.91	1.74	0.79
9	0.99	2.13	0.97
10	1.00	0.00	0.88
11	0.97	0.00	0.90
12	1.00	0.00	0.94
13	0.98	0.00	0.82
14	0.96	0.00	0.79
15	0.97	0.00	0.85
16	0.92	0.00	0.86
17	0.90	0.00	0.75
18	0.94	0.00	1.00
19	0.91	0.00	0.85
20	0.94	0.00	0.90
21	0.91	0.00	0.70
22	0.84	1.42	0.65
23	0.89	1.45	0.66
24	0.84	1.55	0.70

Monthly weighting

Month	elec	heat
January	0.61	0.58
February	0.62	0.56
March	0.84	0.74
April	0.90	0.88
May	0.96	0.92
June	0.88	1.00
July	1.00	0.93
August	0.99	0.93
September	0.96	0.83
October	0.86	0.89
November	0.56	0.94
December	0.53	0.74

TABLE: Daily energy profiles and Monthly weightings.

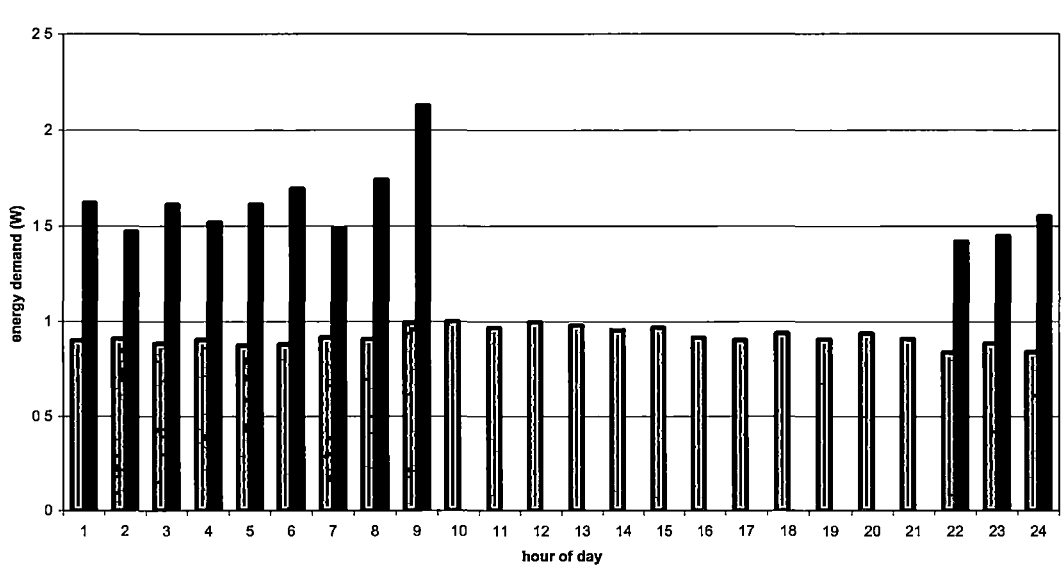


Figure X.X: Daily energy profiles for electrical and 'forced' heating load.

Step 2 - Monthly weighting factors:

The daily load profiles developed above were assumed to represent the 'shape' of energy demands over any day of the year for all activities at the station, but could not be used alone as an accurate representation of the daily load profiles throughout a year. This was due to the variations in the level of demand for heating and electrical power that were known to occur over the different months of the year as a consequence of changes in personnel activities, populations sizes and external conditions.

Consequently, monthly weighting factors for both electrical and heating loads were determined for each month by examining the Mawson station operating data from 2002-2004[2]. This data shows fuel usage and wind power generation for each month of the year for 2002-2004, and most importantly, electrical and heating loads for each month. This data was used to identify the monthly trends in the different load categories.

The original file provided by the AAD included an error where the contribution of wind energy to the station loads was not accurately considered, and consequently the total heating load for the station was falsely represented only by the heat provided from SAB-fuelled boilers or via waste-heat capture from the generator sets. Ultimately, as the amount of wind power generated at the station increased, the total station load appeared to decrease due to the contribution of the wind energy to the heating load not being calculated.

To address this issue and develop an accurate representation of the station's true electrical and heating loads over the year, the assumption was made that the monthly and annual heating demands of the station would remain fairly consistent with the demand in 2002. At this point in time, the heating demand was met passively via waste-heat capture from the gen sets, and actively served by the SAB fuelled boilers when required.

It was further assumed that in the years when the wind turbines where operating, electric boilers would be used to generate heat from surplus wind energy – an additional passive source of heating. The total heating load of the station would therefore be met with waste-heat from the gen sets, surplus wind energy via electric boilers, and SAB-fuelled boilers contributing any additional heat as required. Unfortunately the wind energy data provided did not identify specific contributions to the heating and electrical loads, and expressed only the total amount of wind energy used by the station during each month. The contribution of wind energy to the heating demand of the station for each month was subsequently determined by calculating the difference in the regular (non-wind) heating demand between that month and the reference month in 2002. If the heat demand was less than the reference month, the additional heat required was assumed to be sourced from the wind turbines. If the total amount of wind energy available for the month was insufficient to meet the calculated heating load deficit, all of the wind energy was assumed to contribute to heating and the remaining heat deficit was left unmet. The remaining wind energy contribution was subsequently assumed allocated to the electrical demand of the station. It must be noted that this strategy results in total monthly and annual heating loads for the station that are closely based (almost identical) with the heating demand for 2002. Also, the conversion efficiency of wind energy to heat via electric boilers was assumed to be 100%.

[2] File reference "operation stats 2004"

These actions enabled the total contribution of wind energy to the station load to be apportioned to the heating and electrical loads. This subsequently enabled the calculation of revised total heating and total electrical loads, and total station loads, for the periods of wind turbine operation.

Figure X below illustrates the monthly trends for the electrical, heating and total station loads for the period 2002-2004. The heavier lines indicate the average values over the period for each load category. As noted above, the heating load trends over the period are all similar due to the use of 2002 as a reference year to specify total heating loads for the years using wind energy for additional heating.

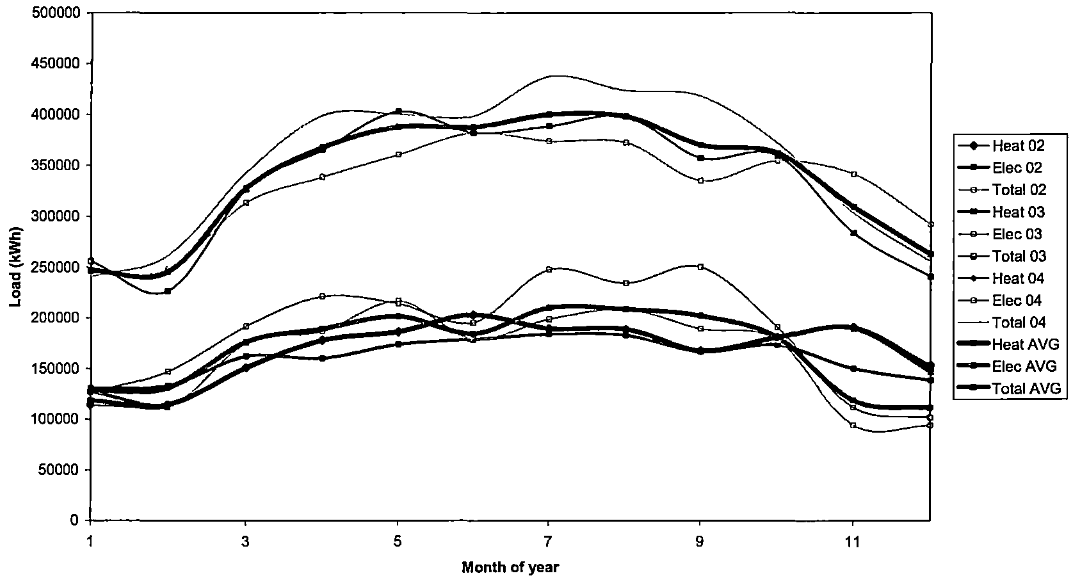


Figure X.X: Monthly summary of the station loads 2002-2004.

The average monthly values for the heat and electrical loads were then normalized against the highest individual monthly load – the electrical load in July. These normalized values were subsequently entered as the monthly weightings in the load file worksheet. These values are included in Table X.X above, and detailed in Figure X.X below.

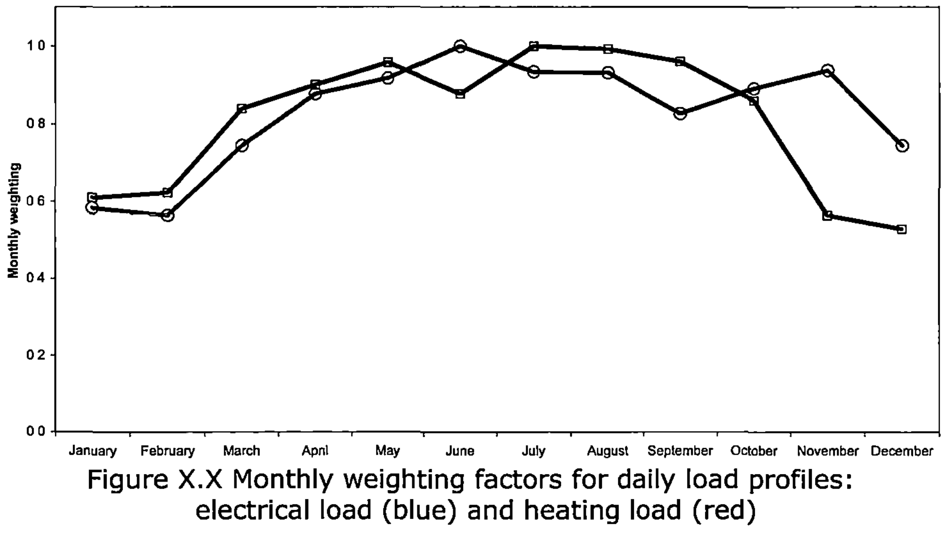


Figure X.X Monthly weighting factors for daily load profiles: electrical load (blue) and heating load (red)

Step 3 - Generation of the load file for the *Conservative approach*:

The load file was subsequently generated by:
Action 1: working with the unforced daily load profiles:
For each individual hour of a day, the normalized electrical and heating loads were each multiplied by their respective monthly weighting, and the individual totals combined. This process was repeated for each hourly time step in the year, based on a standard 28 day month. The largest total load for an individual hour over the year was identified, and used to normalize the annual load profile.

Action 2: working with the forced daily load profiles:
The process of generating an annual load profile via multiplication of the daily electrical and heating loads and the monthly weightings was repeated from step 1, but using the forced daily heating profile instead of the unforced profile. The normalizing factor (largest total load from an individual hour) used in Step 1 (unforced load data) was used to pseudo-normalise the forced annual load profile.

The annual load profiles that resulted from these actions are presented in Figure X.X below.

***Practical approach* to load profile creation**

This approach sought to create a method of simulating the complete Mawson system with a less conservative approach to the hydrogen system design. The assumptions inherent in the conservative approach guaranteed that it would generate an over-sized system design, and this approach aims to gain a more realistic indication of the minimum system sizing.

Preliminary analysis with the conservative approach also indicated that excess wind energy was available within the system even when operating an over-sized hydrogen system. This suggested that it would be possible to assume that the heating needs of the station were met with excess wind energy (and/or CHP from diesel of H2 systems) and did not require direct operation of the hydrogen system. This would enable the model of the wind-H2 system to be simulated only with consideration of electrical loads.

This approach is based on the assumption that effective thermal energy storage solutions can be sourced that would enable the intermittent sources of thermal energy to be absorbed and stored for release upon demand.

The practical approach will generate energy system designs that are a more accurate reflection of the hydrogen energy component sizes that would be required to meet the critical electrical energy demands of the station as a wind-hydrogen system, when compared to the conservative approach. The practical approach, however, does retain some elements of conservatism as the production of electricity from the hydrogen system would produce thermal energy resources that are not accounted for in the model. The practical approach is also more relevant to contemporary station operations, whereby diesel boilers and an auxiliary (emergency) power house are available on station in the event of failure or inadequacy of the existing system. The diesel boilers in particular could be efficiently utilised to meet any deficit in thermal energy demand, and represent a more efficient use of imported diesel fuel than use in CHP electric generators.

The load profile for the practical approach was developed by utilising the daily load profile and monthly weightings for the station's electrical load that were produced for the conservative approach. Consequently, the practical approach makes no consideration of thermal demands for the simulation process.

The annual load profile for the practical approach is presented in Figure X.X below.

Identifying maximum load values

The above actions provided normalized (0 to 1) annual load profiles for the simulations that were incorporated into a 'location file' for Mawson station. These profiles, however, gave no indication of the absolute magnitude of the energy demands met by the energy system. These maximum load details were entered by the modeler via the 'energy system interface' detailed in Figure X.X above.

The maximum load details for the station's operation were calculated from data provides by the AAD ([3]) for 1999 - a maximum total load of 480 kW and electrical-only load of 275 kW.

Substantial efforts at improving the efficiency of energy use have been undertaken at the station since the collection date of the data, resulting in improvements of 20% reduction in total energy demand and 30% reduction in electrical energy demand.

If these assumptions exaggerate the achievements in energy reduction at the station or consumption rises above existing levels, analysis of 110% of the load value will provide an indication of relative performance. Similarly, if further reductions in energy demand can be achieved in the future, analysis of a 90% load value may provide a more accurate representation.

The maximum load values subsequently used for the conservative and practical approaches to simulating the operation of Mawson station with a wind-hydrogen energy system are detailed in Table X.X below.

	Conservative load (kW) – combined heating and electrical	Practical load (kW) – electrical only
100%	400	200
90%	360	180
110%	440	220

Table X.X Magnitude of thermal and electric loads for Mawson station.

[3] file ref: Mawson staion load

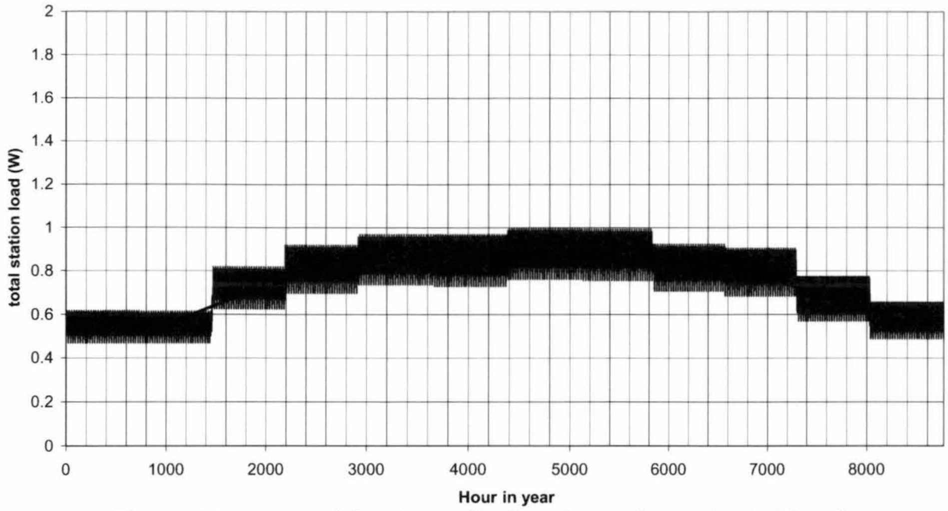


Figure X.X Annual load profile for the unforced total load.

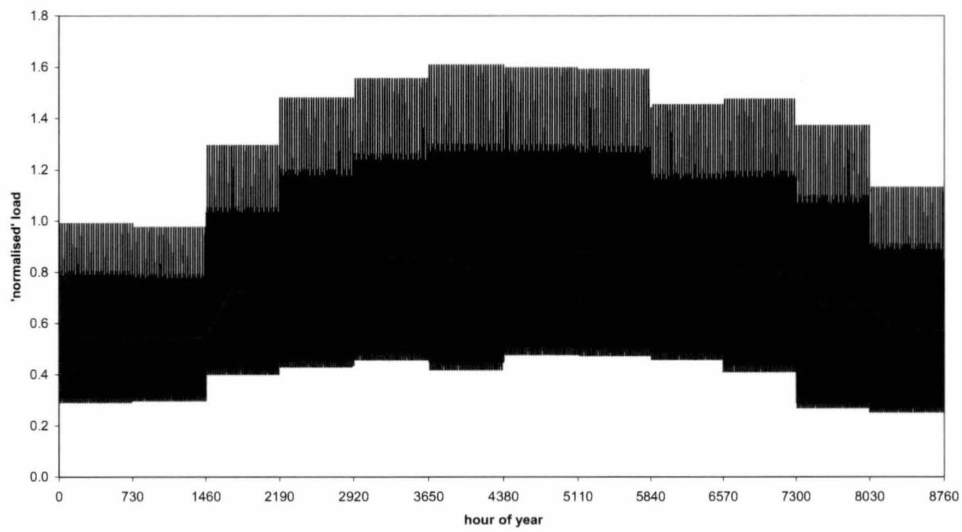


Figure X.X Annual load profile for the conservative approach - forced total load.

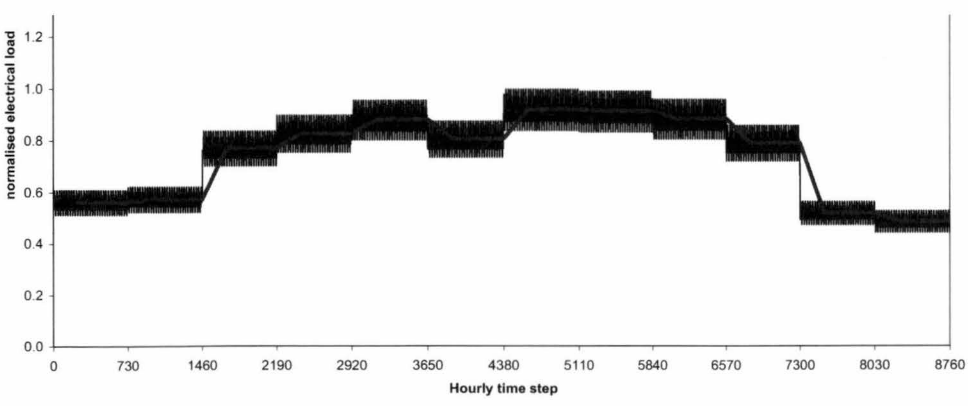


Figure X.X Annual load profile for the practical approach - electrical load only.

2.2.2 *Generation of wind speed data*

Simulation of a wind-hydrogen energy system requires the input of data relating to the raw wind energy 'resource' that is available at the site. To model Mawson station with the chosen simulation tool, hourly wind speed (m/s) data measured at 30m height was required.

Fortunately, some of the earliest research activities undertaken at Antarctic stations include the recording of weather conditions, resulting in a long history of wind speed measurements at Mawson. A range of weather files were sourced from the AAD, but unfortunately, none provided a complete data set of adequate format for the simulation effort (hourly wind speed for an entire year). A representative data file therefore had to be compiled from several data sets.

The data sets provided included:

1. 10 minute weather data sets for February to December 2003 (incomplete), and December 1998 - May 1999 (incomplete), measured at 30 m.
2. High resolution (1 second) weather data sets for the years 2001, 2002, 2004 and 2005 (not 2003) (incomplete sets).
3. Also, low resolution (3 hour) data set for 44 years (1955-1998) and statistical analysis of this data.

The 2003 data set was assessed in collaboration with AAD personnel to be the best quality and most suited to the application, and formed the basis of the compiled data set used in the simulation.

The actions to compile the data set began with analysis of the 2003 10 min data set to identify missing data points. These gaps were subsequently filled by extracting data from the 1998-1999 10 min data set to fill the large holes (eg January 2003); or by synthesizing data from the surrounding days to fill data gaps in the order of days or hours. Data that was imported from 1999 was scaled to ensure consistency with the existing 2003 data set. This scaling factor was determined by calculating the average wind speed for each month (at 10 m heights) using the available 2003 unprocessed data set. These monthly averages were then compared with their corresponding historic monthly average speeds, as calculated from the 44 year data set (also at 10 m height). This analysis provided a weighting factor with which the 2003 and 1999 monthly data sets were then multiplied to normalize their average monthly speeds (at 30m heights) with the historic average (see Table X.X below).

Monthly averages summary

	2003	historic	weighting
January		9.18	0.9376
February	14.4183	11.19	0.7761
March	13.39828	12.04	0.8986
April	11.12278	11.36	1.0213
May	11.20226	11.63	1.0382
June	14.41951	12.11	0.8398
July	11.60901	11.82	1.0182
August	12.15664	12.08	0.9937
September	12.96674	11.53	0.8892
October	12.18416	11.26	0.9242
November	10.67567	11.26	1.0547
December	10.74359	9.23	0.8591
average	12.26336	11.22	0.9376

Table X.X: conversion factors to generate a 'typical year' wind profile.

The resulting data set of wind speeds at 30m heights and 10 minute time intervals for a 'typical' year was further processed to reduce the time resolution to hourly intervals, a reduction in data points from 52560 to 8760. This was achieved by processing the file with a fortran90 program which calculated the average wind speed from the six 10 minute readings per hour (program developed by Ulleberg).

These actions resulted in a viable data set for the simulations that was based on a specific year (2003) but also, in theory, represented a 'typical year'. The annual wind speed profile for this year is presented in Figure X.X below. This hourly time-step data series was combined with the relevant load profiles (conservative or practical) for the formation of specific 'location files' for use in the simulator.

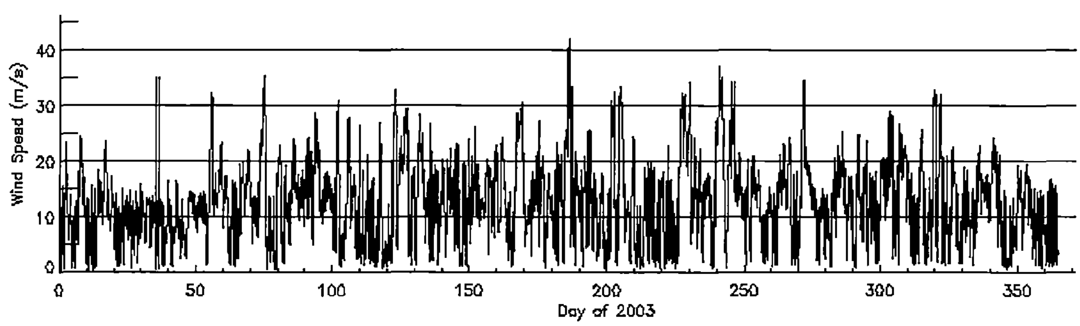


Figure X.X: 2003 (reference) wind speed data set

Comparison of the 2003 data set with historic trends

Executing the simulations for Mawson station with the 2003 (reference) data set was expected to yield a useful outcome for the user community as the simulations would be based on genuine user load and wind energy data. However, evaluating the viability of an energy system developed with that to perform in other wind conditions was not be possible without further analysis of the relationship between the 2003 data set and wind data from other years.

The availability of 44 years of historic data for the site provided a unique opportunity to investigate the long term trends in wind behaviour at Mawson. Previous analysis of the historic wind patterns was completed by AAD personnel (and consultants) during the evaluation of wind turbines for energy generation at Mawson station. This analysis, however, didn't consider the performance of this historic data relative to the specific 2003 reference file.

In order to undertake this evaluation, the raw data for the 44 years (3 hourly measurements at 10m height) was processed through a spline-fitting program to generate data at hourly time steps. The spline-fit also addressed the issue of gaps in the data and corrected incidents of negative wind speeds via conversion to zero. This action was undertaken by Dr Kelvin Michael, primary supervisor for the PhD. The time-step modified data then needed to be converted to a 30 m measurement height to enable direct comparison with the reference file.

Although a wide range of factors are known to influence the speed of a wind event when measured at different heights, including surface and terrain roughness, surrounding buildings, and air temperature and density, this research sought a single and experience-based conversion factor to apply to the historic data. To achieve this, the available raw data for 2003 with 10 minute time steps (approximately 41500 time steps) was compared for the measurement heights of 10 m and 30 m. A detailed comparison of wind speeds at the two measurement heights, including 10 day moving-average trend lines, is presented in Figure X.X below (for first 5000 minutes of year). This graph illustrates the consistent trends between the two measurement heights, but also the increased variation between the two data sets at higher wind speeds.

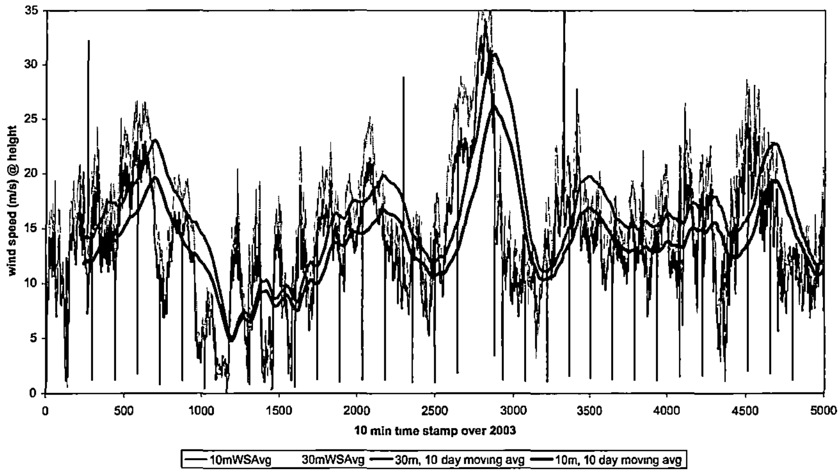


Figure X.X: comparison of 10 m and 30 m raw data (@ 10 minutes)

A conversion factor between the two measurement heights was subsequently determined by calculating the relationship between the average annual wind speeds at each height, as detailed in Table X.X below. An alternate theoretical approach to wind speed height conversion was used to confirm the validity of this approach.

30 m average wind speed (m/s):	13.76
10 m average wind speed (m/s):	12.08
Conversion factor: 10m to 30m	1.14

Table X.X: height conversion factors for 2003 data

The accuracy of the conversion factor for manipulating data measured at 10 m height for comparison with data measured at 30 m height is presented over a 200 minute time period in Figure X.X below. The graph illustrates that converted 10 m data is highly comparable to the raw 30 m data, but peaks within the data sets are slightly exaggerated for the converted data. Therefore, applying the conversation factor developed with the 2003 data to the historic data (measured at 10 m height) will produce historic data that is generally comparable but may have peaks slightly higher than should be expected.

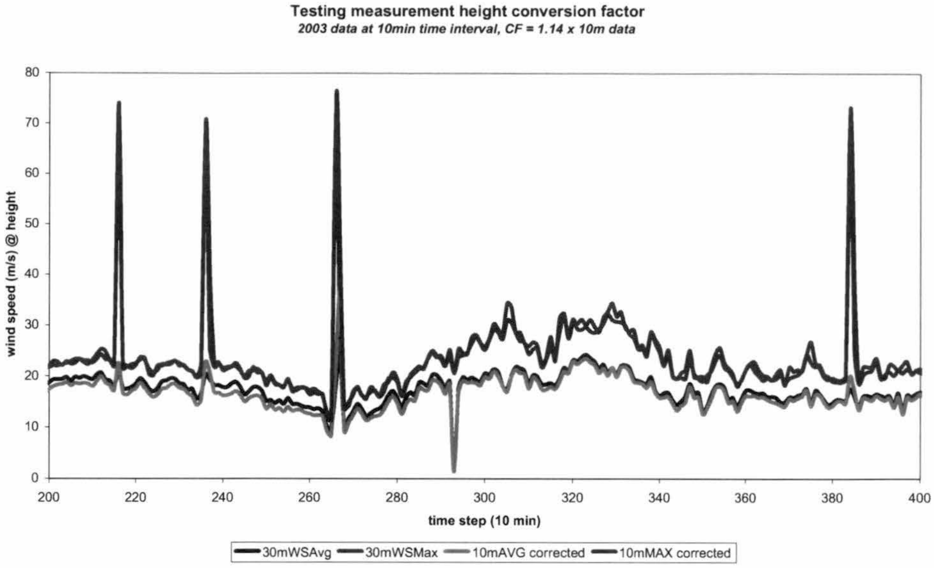


Figure X.X: testing the measurement height conversion factor

This conversion factor was subsequently applied to the previously spline-fit historic data to produce a comprehensive collection of wind speed data sets for a 44 year period that were suitable for comparison with the 2003 (reference) data set. This series of data is presented graphically in Figure X.X below.

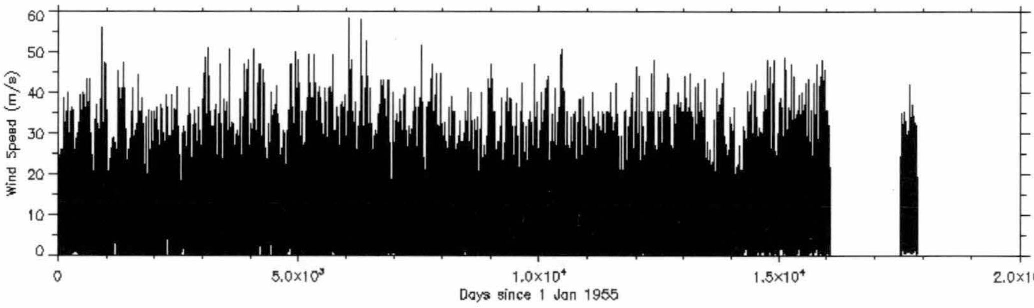


Figure X.X: 1956–1998 + 2003 wind series for Mawson station @ 30 m height

Comparison of the 2003 data set with the data for the other 44 years is presented in Figure X.X following, including the hourly average and maximum and minimum data points for each hourly interval. This comparison includes polynomial trend lines for a broad scale trend analyses and a 10 day moving average for the 2003 data.

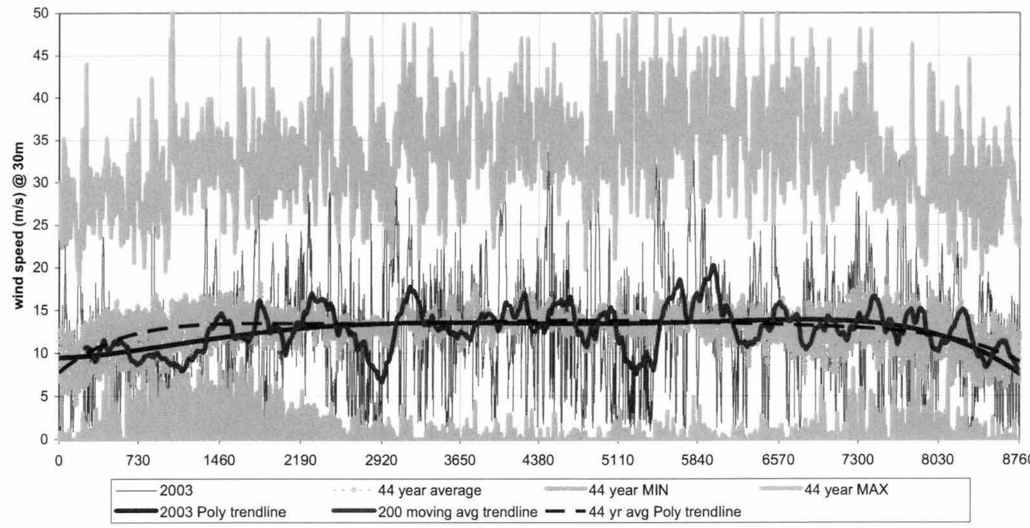


Figure X.X: comparison of historic and reference wind speed patterns at Mawson

The polynomial trend lines were selected based on a review of each of the 44 years of historic data which indicated that most years had 3-6 major inflection points in the plotting of their annual wind speed profile. Consequently a sixth order polynomial would enable a viable comparison of the two data sets. Although the polynomial trend line (with six points of inflection) is a crude approximation of the information contained in the detailed data sets, it is adequate to represent the very broad trends in the data. An appropriate use for the 2003 polynomial trend line (dark blue line) is a comparison with the broad trends in the 44 year average, calculated as the average value over the 44 years for each hourly time step over an annual cycle. This 44 year average (yellow line) is very similar in profile and magnitude as the 2003 polynomial trend line, indicating that the broad trends in the 2003 data have a close correlation with the average behaviour of the wind speeds over 44 years. In other words, 2003 is quite an average year from a broad or low resolution perspective. The equivalent sixth order polynomial trend line for the 44 year average (dashed black line) reinforces this assessment, and contributes the additional information that the 2003 data set exhibits a slightly lower than average annual first quarter and could be ending the year with similarly below average wind speeds.

A higher resolution analysis of the relative behaviour of the 2003 and historic data sets is presented with the moving average trend line (coloured red). This tool presents the moving average of the wind speed data over a rolling period of 10 days (240 data points). This action effectively smooths the more extreme peaks and troughs of wind speed that occur over shorter time periods while ensuring that the broader trends in the data are represented. Comparison of this trend line with the 44 year average data confirms that the 2003 data correlates well with the historic data, except for potential anomalies at 2900, 5500 and 5900 hours. These anomalies suggest a possible departure in behaviour from the very broad trends in wind speed over the past 44 years, however, the absence of movement by the raw 2003 data outside the existing range of maximum (MAX) and minimum (MIN) values reduces the potential for such behaviour.

Comparisons of the 2003 moving average trend line and the individual annual wind speed profiles for each of the 44 year data sets provided a further method to determine if 2003 is a normal or abnormal year. This comparison also provided an opportunity to identify the different 'types' of years that may occur and give an indication of a good or poor years for wind characteristics. 11 separate years of interest were selected to represent the broad range of possible annual wind profiles, and are examined in further detail in Appendix X. General characteristics of each of these representative years are reviewed in Table X.X below.

1957	generally low, and very low at end of year
1958	start lowest, single winter peak (in middle of range), low end of year
1961	peak early in the year then decays for rest of year
1970	generally high and flat - average high year
1971	highest, single winter peak (maximum)
1982	generally poor year, mid year slump (not peak) but overall quite flat
1983	mid year trough but peaks either side, four inflections
1991	generally high and flat - average high year
1993	flat and low
1997	flat and mid
1998	average throughout year, except for having 5 inflections, very low at end of year

Table X.X: brief details of 11 years with interesting wind speed profiles

The conclusion from the analysis of the 2003 data set was that it represented a 'fairly normal year' – one that was not particularly encouraging for wind power generation as it exhibits some periods of abnormally low winds (2900 hours) and a suggestion of leading into a poor summer (8700 hours). However, it is persistently within the bounds of past experience. Consequently it can provide a genuine and unique annual wind profile that doesn't exceed precedents established by other years and has an average wind speed that conforms well with an historic average. Using it as a representative year for simulations provides the benefits of using real data for a 'normal' and not too good year, thereby ensuring that natural levels of variation in included in the data.

Further analysis of wind speed data is presented in Appendix X, including:
1. evaluation of the potential impact of extrapolating the historic data from 3 hourly data points to an hourly data set for comparison with the 2003 data, including possible loss of 'gusty' wind speed peaks.
2. confirmation that daily peaks in wind speeds are concurrent with even periods of high heating loads.

2.2.3 *Generation of 'power curve' for wind turbines*

As the wind turbines installed at Mawson station are modified versions of commercially available turbines (Enercon E-30), the algorithm relating power generation capability to wind speed had to specifically developed for integration into the modeling toolbox. A 'best guess' power curve for the turbines was supplied by the AAD and appropriately formatted for use in the simulations.

2.2.4 *Generation of 'location' files for modeling toolbox*

The hourly load profiles (conservative and practical) and wind speed data for 2003 developed through the above actions were subsequently combined into two specific 'location' files for use in the modeling toolbox. Each file was a three column data set in the format of an hourly time step and corresponding values for the normalised load (conservative or practical) and wind speed.

2.3 Detailed analysis of the modelling process

Having made the necessary modifications to the modeling toolbox and created the required input data sets, simulation and analysis of the wind-hydrogen energy systems proposed for Mawson station was initiated. The process that was followed in initiating, running and evaluating simulation sequences is reviewed in the following pages.

The simulation process began at the 'primary toolbox interface' detailed in Figure X.X above. At this interface, the user selected an energy system design from the three options included in the toolbox (as detailed in Figure X.X above). This launched the relevant energy system interface (Figure X.X) where the user input relevant key parameters and variables for the simulation. The full list of potential variables and parameters, with supporting descriptions, is detailed in Table X.X following. Components that are not included in a system do not appear in the interface for that system; for example, a diesel electric generator (DEG) is not used in System 1 and so does not appear in the interface for that system.

Variables and parameters were manually entered in the relevant fields of the interface. Values for the fixed parameters and some variables were determined through analysis of recent publications that detailed performance characteristics of components (e.g. HSAPS study) and discussion with experts in the field (primarily Ulleberg at IFE). Other values, such as fuel cell or generator power ratings, were initially determined through practical consideration of the energy system demands (i.e. power generation capability of the non-wind components must be sufficient to meet the peak station load and parasitic loads from devices such as the electrolyser).

The computation process for the simulation was initiated from the energy system interface, automatically calling the relevant TRNSYS model. An individual simulation took up to 5 seconds to complete on a common laptop computer. Progress of the simulation was assessed through the presentation of key data sets (such as hydrogen storage state of charge) on a graphical TRNSYS output screen. If the simulation was successfully completed for a full calendar year, a TRNSYS output file was automatically generated and stored to disk.

For some design configurations, the simulation failed part way through the year due to numeric/calculation faults. Discussions with Ulleberg indicated that these failures were a result of conflicts within the energy system's control strategy. Addressing the faults would require manipulation of the core commands in the control strategy – a level of involvement with the modelling tool architecture that was beyond the functionality of the toolbox, requiring expert input. As detailed later, became an issue for some simulations resulting in the termination of experimentation.

Analysis of the TRNSYS graphical output screen at the end of a simulation provided an opportunity for initial evaluation of the system configuration – clear signs of poor system design included obvious depression in H2 SOC below minimum levels (requiring energy import) and/or a relative decay in the system SOC between the start and end of year. Failing these minimum tests prompted modification of one (or more) variables via the energy system interface and re-running of the model. If the simulation result passed these initial tests, the user returned to the primary toolbox interface to initiate the transfer of the model results (TRNSYS output file) to the primary interface. Once transferred, the interface automatically undertakes a variety of post-simulation calculations with the output data, presenting them in numerical format on the main interface screen or through a number of graphs. The first test for a successful system design was the requirement for 'imported energy' to the system. This information is expressed in terms of MWh/year and % of total energy input. Most simulations sought to design an energy-independent system, therefore requiring zero imported energy. The second test for a viable system design was the hydrogen storage SOC, assessed through a graph of storage over the year. This indicated whether the hydrogen storage levels were balanced at the start and end of year, and if the storage reservoir was being utilised to full capacity.

Failure to meet these tests again prompted carefully considered changes to one or more variables in the simulation, and re-running of the model.

For system designs that passed these secondary tests, the designs were classed as viable but not optimised, indicating that the system would meet the performance requirements but did not represent the best possible configuration of component sizes. The simulation process was subsequently repeated, with carefully considered variations to selected components made with an objective of reducing the size of each component to a minimum level while meeting the system performance requirements. This second process of variable iterations resulted in the identification of optimised system designs. A summary of the complete system design and optimisation process is detailed in Table X.X below.

1. Successful completion of simulation for a calendar year 2. Zero demand (or specified levels) for energy import into the system 3. Balanced levels of hydrogen storage at the start and end of year 4. Maximum use of the hydrogen storage reservoir 5. Minimum sizes for all components

Table X.X: Summary of system design and optimisation process

In practice, one approach that was routinely taken at the start of a new system design to minimise the impact of some component variables was to set the hydrogen storage capacity to a moderately high level. This reduced the likelihood of the system running out of stored hydrogen and requiring energy import. The power generation components (HEGS and FC) were then sized to meet the maximum station load, with additional capacity dependent on the rated power and idling power of the electrolyser. The electrolyser size subsequently became the critical component in ensuring the hydrogen storage SOC performance requirements were met. Modifications to the electrolyser size influenced hydrogen production rates over the year, and the capacity of the HEGS and/or FC to meet the parasitic (idling) load of the electrolyser. Variations to the HEGS/FC rated power subsequently influenced the rate and volume of hydrogen consumption during operation and idling. These two factors influenced the fill and discharge rate of the hydrogen storage, with other factors in the energy equation (user load and power generation from wind turbines) remaining constant. Variations to the initial SOC of the hydrogen storage also provided a means of balancing the storage levels at the start and end of year. The hydrogen storage volume could then be reduced to an optimum level and the sizes of the other components also re-assessed. This process reduced the time taken to both identify viable system designs and to optimise the system designs.

Optimised system designs were then assessed further, including consideration of the availability of excess energy and the duty cycle of components such as electrolyser, fuel cell, and hydrogen electric generator.

Table X.X: System parameters and variables specified by the user in the wind-hydrogen energy system toolbox.

Simulation Input file		
Location	Variable	Enables user to select from various location files that have been prepared by the user – each file specifies the annual hourly (normalised) load profile and wind data for a site. Enabled specification of electric-only or electric-and-heating loads with the same wind data set for Mawson station.
Peak load (kW)	Variable	Specifies the peak load that relates to the normalised load profile included in the location file.
Wind Energy System		
Type	E30 (polar)	Enables user to select from a list of turbines – requires the user to include the 'power curve' for the turbine in the model infrastructure.
# of turbines	3	Number of turbines used in design. Based on the number of turbines originally planned for use at Mawson station (only 2 currently installed).
Hydrogen Energy System		
Electrolyser		
Rated power (kW)	variable	Rated power demand for electrolyser inverter. Primary variable for this component. Influences the amount of hydrogen produced and operating power demands.
Minimum idling power (%)	Variable	Secondary variable for this component. Influences the amount of power consumed when system idling compared to rated power.
Off-switching set point (%)	99	Level of storage state of charge (SOC) at which electrolyser will stop production. Influences effective use of storage volume and potential for dumping of hydrogen (electrolyser still produces when idling).
On-switching set point (%)	80	Level of storage SOC at which electrolyser will start production. Influences number of start-stops.
Fuel Cell		
Rated power (kW)	Variable	Primary variable for this component. Influences power generation capability from stored H2, and parasitic hydrogen consumption during idle.
Minimum idling power (%)	5	Influences parasitic hydrogen consumption and capability of system to respond quickly. Idling power value assumes system switches off and requires 5 minute start-up / hour at operating efficiency (5/60*50% = 4.1, rounded to 5%)
Off-switching set point (%)	20	
On-switching set point (%)	10	
H2 storage		
Max. allowable pressure (bar)	200	Maximum allowable pressure in H2 storage. Influences the amount of hydrogen stored in the physical volume and the potential for release of excess H2. also influences losses from compression of hydrogen gas.
Physical volume (m^3)	Variable	Primary variable for this component. Influences the amount of physical space for H2 storage under pressure, and total effective amount of energy stored.
Initial state of charge (%)	Variable	Minor variable for this component – influences initial amount of hydrogen storage, but key element is system must balance at the end of year.
Hydrogen Electric Generator		
Rated power (kW)	Variable	As per fuel cell.
Minimum idling power (%)	0	As per fuel cell. Assume can be shut down when not in use.
Diesel Electric Generator		
Rated power (kW)	Variable	Primary variable for this component. Influences power generation capability from stored diesel fuel, and parasitic diesel consumption during idle.
Minimum idling power (%)	0	Influences parasitic fuel consumption and capability of system to respond quickly.

Many other parameters and variables are used in the modelling toolbox, but are hidden in the architecture of the models and can only be accessed through the original TRNSYS project models. For reasons relating to commercial sensitivity and the significant quantity of intellectual property invested in their development, these original models are not included in the modelling toolbox.

Three important characteristics of the energy systems in the models can influence the operation and outcomes of the simulations. The impacts of these characteristics are evaluated through calculation of the factors reviewed in Table X.X below. The characteristics include:

1. Inclusion of an inverter on the output side of the fuel cell for conversion of DC power to AC; this inverter has an efficiency of 87%, reducing the effective generating capacity of the component.
2. The hydrogen and diesel electric generators do not include inverters in their operation and so do not have additional efficiency losses in power output.
3. the inclusion of an inverter on the input side of the electrolyser for conversion of AC power to DC, with an efficiency of 87%. This raises the effective power demand of the component beyond the rated level.

MIN generation need (kW)	Considers the maximum user load and the true electrolyser idling load (idling power rating (%) * rated power demand of electrolyser and inverter losses (%))
MAX generation need (kW)	Includes the full user load and true electrolyser operating load (rated power demand of electrolyser and inverter losses (%))
Real H2 gen cap (kW)	Includes the true fuel cell power generation capability (rated power less inverter losses) + full HEGS rated power (and DEGS rated power for system 2)

Table X.X: mechanisms to analyse the impacts of inverters in the systems

Several important assumptions relate to the operation of the models, including:

1. System assumes the existence of suitable power electronics components to enable the short-term storage of energy to enable the start-up of components that are in idle or off modes.
2. The DEGS and HEGS components can be switched off when not required.
3. The FC can be effectively switched off, but requires a five minute start up time due to the higher operating temperatures required (compared to the DEGS/HEGS which can be shut off).
4. Storage system cannot go below a state of charge of 10% as safety factor for real-world operations.

The basic control strategy elements that apply to the operation of each of the wind hydrogen systems include:

1. User load and parasitic energy demands (electrolyser) will be met with energy generated by the wind turbines (WECS) as much as possible.
2. Any deficit in the wind energy relative to the load will be met first with the HEGS (or DEGS) component. If the user load exceeds the combined generation capabilities of the WECS and HEGS, the fuel cell will be used to meet the remaining demand.
3. If excess wind energy is available and sufficient to operate the electrolyser beyond idle capacity, the electrolyser will start producing hydrogen (unless the storage tank is full).
4. Excess energy from the WECS that is not used for hydrogen production and from the idling operation of the HEGS/DEGS/FC will be classed as 'export' energy.
5. The electrolyser and fuel cell will consume power and hydrogen respectively at all times during the year due to idle power demands.

2.4 *Detailed analysis of experimental modelling results*

This section presents an example of the detailed method used to analyse the results of the energy system modelling. The process was utilised for each of the issues examined in the research. The summarised version of all of the results is presented in Chapter 8.

2.4.1 *Review of experimental program*

A series of model scenarios were developed to assess the following parameters:

1. Practical and conservative approaches to developing load profiles for the thermal and electric energy demands at Mawson station
2. Operation of the station as a 100% 'energy independent' facility, and a more pragmatic approach that allowed approximately 25% import of energy. This second approach recognised that imported energy resources (e.g. diesel) would be available at the site for a reasonable period in the future as a back-up service and to meet other energy demands (transport).
3. Three energy system designs using a range of conventional and emerging hydrogen energy technologies, and the integration of existing (diesel) energy services into the wind-hydrogen system.
4. Two settings for the idling load of the electrolyser relative to the rated power (EIL) - a conventional value of 40% and a more optimistic value of 10% to give an indication of how improvements in electrolyser performance could influence the overall system design.
5. Reference load values for the conservative and practical load profiles, and evaluation of the potential impacts of 10% variations (increase/decrease) in the station load(s).

The complete series of simulations that were undertaken are detailed in Table X.X below. As illustrated by this list, the modelling process ultimately focused on the application of system 3 from the modelling toolbox with the practical load profile. This system was the most developed and proven resource in the toolbox due to its original application in developing a wind-hydrogen system for a remote Norwegian that has many similar characteristics to the Mawson scenario. The modelling process utilised the 2003 (reference) wind speed data set developed above, and the wind turbine power curve provided by the AAD for the Enercon E-30 (polar rated) device.

Practical load	100 % independent operation	System 3	40 % EIL	180 kW
				200 kW
				220 kW
			10 % EIL	180 kW
				200 kW
				220 kW
		System 1	40 % EIL	200 kW
	80% independent operation	System 2	40 % EIL	200 kW
Conservative load	100 % independent operation	System 3	40 % EIL	200 kW

Table X.X: Experimental program for the computer modelling of wind-hydrogen energy systems at Mawson station, Antarctica.

Results from experiments with the *practical* load profile:

Elyzer idling power (%) (rel. to rated power)	40	10	Elyzer comparison 10 to 40 (% Δ)	40	Load comparison to 200 kW (% Δ)	10	Load comparison to 200 kW (% Δ)	Elyzer comparison 10 to 40 (% Δ)	40	Load comparison to 200 kW (% Δ)	10	Load comparison to 200 kW (% Δ)	Elyzer comparison 10 to 40 (% Δ)
Component specs													
Peak load (kW)	**200**	**200**	0	**180**	-10	**180**	-10.0	0.0	**220**	10	**220**	10.0	0
Elyzer rated power (kW)	356	189	-46.9	295	-17.1	158	-16.4	-46.4	455	28	212	12.2	-53.4
FC rated power (kW)	150	89	-40.7	125	-16.7	80	-10.1	-36.0	205	37	100	12.4	-51.2
HEGS rated power (kW)	275	150	-45.5	250	-9.1	140	-6.7	-44.0	300	9	164	9.3	-45.3
Total gen capacity (kW)	425	239	-43.8	375	-11.8	220	-7.9	-41.3	505	19	264	10.5	-47.7
H2 storage vol (m^3)	375	259	-30.9	310	-17.3	220	-15.1	-29.0	490	31	295	13.9	-39.8
Component evaluation													
MIN gen need (kW)	360.91	221.36	-38.7	313.34	-13.2	197.85	-10.6	-36.9	425.66	18	243.96	10.2	-42.7
MAX gen need (kW)	602.28	413.57	-31.3	513.35	-14.8	358.54	-13.3	-30.2	734.15	22	459.56	11.1	-37.4
REAL H2 gen cap (kW)	405.5	227.43	-43.9	358.75	-11.5	209.6	-7.8	-41.6	478.35	18	251	10.4	-47.5
REAL vs. MIN (%)	12.4	2.7	-9.6	14.5	2.1	5.9	3.2	-8.6	12.4	0.0	2.9	0.1	-9.5

Elyzer idling power (%) (rel. to rated power)	40 corrected	10	Elyzer comparison 10 to 40 (% Δ)	40 corrected	Load comparison to 200 kW (% Δ)	10	Load comparison to 200 kW (% Δ)	Elyzer comparison 10 to 40 (% Δ)	40 corrected	Load comparison to 200 kW (% Δ)	10	Load comparison to 200 kW (% Δ)	Elyzer comparison 10 to 40 (% Δ)
Component specs													
Peak load (kW)	200	**200**	0	**180**	-10	**180**	-10.0	0.0	**220**	10	**220**	10.0	0
FC rated power (kW)	100	89	-11.0	87.5	-12.5	80	-10.1	-8.6	143.5	44	100	12.4	-30.3
Total gen capacity (kW)	375	239	-36.3	337.5	-10.0	220	-7.9	-34.8	443.5	18	264	10.5	-40.5
Component evaluation													
MIN gen need (kW)	360.91	221.36	-38.7	313.34	-13.2	197.85	-10.6	-36.9	425.66	18	243.96	10.2	-42.7
MAX gen need (kW)	602.28	413.57	-31.3	513.35	-14.8	358.54	-13.3	-30.2	734.15	22	459.56	11.1	-37.4
REAL H2 gen cap (kW)	362	227.43	-37.2	326.13	-9.9	209.6	-7.8	-35.7	424.85	17	251	10.4	-40.9
REAL vs. MIN (%)	0.3	2.7	2.4	4.1	3.8	5.9	3.2	1.9	-0.2	-0.5	2.9	0.1	3.1

Note: '40 corrected' data presented for system 3, 40% EIL with FC rated power reduced by 30%.

Table X.X: Component size data for System 3, with comparison of electrolyser idling loads of 10% and 40% (model data and corrected model data).

Table X.X: System design and performance indicators for System 3, with comparison of electrolyser idle operating loads of 10% and 40% (of peak load).

Elyzer idling power (%) (rel to rated power)	40	10	Elyzer comparison 10 to 40 (% Δ)	40	Load comparison to 200 kW (% Δ)	10	Load comparison to 200 kW (% Δ)	Elyzer comparison 10 to 40 (% Δ)	40	Load comparison to 200 kW (% Δ)	10	Load comparison to 200 kW (% Δ)	Elyzer comparison 10 to 40 (% Δ)
Energy Balance													
WECS (MWh/yr)	4721	4721	0.0	4721	0 0	4721	0 0	0 0	4721	0.0	4721	0.0	0.0
Energy from WECS %	87	94	7	89	2 0	95	1 0	6 0	84	-3 0	93	-1.0	9.0
HEGS (MWh/yr)	589	249	-57.7	492	-16 5	219	-12 0	-55.5	716	22	282	13.3	-60 6
Energy from HEGS %	11	5	-6	9	-2.0	4	-1 0	-5 0	13	2.0	6	1.0	-7 0
FC (MWh/yr)	101	62	-38.6	73	-27 7	50	-19 4	-31 5	168	66	71	14.5	-57.7
Energy from FC %	2	1	-1	1	-1.0	1	0 0	0 0	3	1.0	1	0.0	-2 0
Total in/output (MWh/yr)	5411	5031	-7.0	5286	-2.3	4989	-0 8	-5 6	5604	4	5073	0.8	-9.5
User load (MWh/yr)	1307	1307	0.0	1176	-10 0	1176	-10 0	0 0	1438	10	1438	10.0	0.0
Energy to user load %	24	26	2	22	-2.0	24	-2 0	2 0	26	2.0	28	2.0	2.0
Elyzer (MWh/yr)	2801	1359	-51.5	2356	-15 9	1161	-14 6	-50.7	3475	24	1507	10.9	-56.6
Energy to Elyzer %	52	27	-25	45	-7.0	23	-4 0	-22.0	62	10.0	30	3.0	-32.0
Energy excess (MWh/yr)	1305	2366	81 3	1754	34 4	2652	12.1	51.2	693	-47	2129	-10.0	207 2
Energy excess %	24	47	23	33	9.0	53	6 0	20.0	12	-12 0	42	-5.0	30.0
Mass Balance													
Elyzer production (Nm^3/yr)	574955	270338	-53 0	481133	-16 3	235952	-12 7	-51 0	715779	24	304803	12 7	-57.4
Fuel cell (Nm^3/yr)	65746	41327	-37.1	46367	-29 5	32331	-21 8	-30 3	112630	71	47465	14 9	-57.9
H2 to fuel cell (%)	11	15	4	10	-1.0	14	-1 0	4 0	16	5.0	15	0.0	-1 0
FC value (kWh/Nm3)	1.5362	1 5002	-2.3	1.5744	2.5	1 5465	3.1	-1 8	1.4916	-3	1.4958	-0.3	0.3
HEGS (Nm^3/yr)	515405	230760	-55.2	437241	-15 2	204880	-11 2	-53.1	613802	19	259457	12 4	-57.7
H2 to HEGS (%)	88	85	-3	90	2.0	86	1 0	-4 0	84	-4 0	85	0 0	1.0
HEGS value (kWh/Nm3)	1.1428	1 079	-5.6	1.1252	-1.5	1 0689	-0 9	-5 0	1.1665	2	1.0869	0.7	-6.8
Dumped H2 (Nm^3/yr)	1997	0	-100 0	4244	112.5	19	-	-99 6	0	-100	0	-	-
Dumped H2 (%)	0	0	0	1	1 0	0	0 0	-1 0	0	0.0	0	0.0	0.0
Deficit of H2 (%)	1.42	0 65	-0.77	1.4	0 0	0.54	-0 1	-0 9	1.49	0.1	0 7	0.0	-0 8
REF DEGS L/year	435668	435668	0 0	392101	-10 0	392101	-10 0	0 0	479235	10	479235	10.0	0.0

	System 3 200 / 40	System 1 200 / 40	Compare S1 to S3 (% Δ)
Component specifications			
Peak load (kW)	**200**	**200**	0
Elyzer rated power (kW)	356	320	-10.1
FC rated power (kW)	150	570	280.0
HEGS rated power (kW)	275	0	n/a
Total gen capacity (kW)	425	570	34.1
H2 storage vol (m^3)	375	365	-2.7
Component size evaluation			
MIN gen need (kW)	361	345	-4.5
MAX gen need (kW)	602	562	-6.8
REAL H2 gen cap (kW)	406	496	22.3
REAL vs. MIN (%)	12	44	31.5
Summary Energy Balance			
Total input/output (MWh/yr)	5411	5472	1.1
Energy to user load (MWh/yr)	1307	1307	0.0
Energy to user load %	24	24	0.0
Energy excess (MWh/yr)	1305	1590	21.8
Energy excess %	24	29	5.0
Component performance evaluation			
Electrolyser			
% time at idle / off	35	32	-3
% time at 90-100% load	57	60	3
Total operating hours	8760	8760	0
Elyzer output energy (MWh/yr)	2801	2574	-8.1
Consumption of system load (%)	52	47	-5
Fuel Cell			
% time at idle / off	89	71	-18
% time at 90-100% load	0	0	0
Total operating hours	8760	8760	0
FC input energy (MWh/yr)	101	751	643.6
Contribution to energy input (%)	2	14	12
HEGS			
% time at idle / off	69	n/a	n/a
% time at 90-100% load	17	n/a	n/a
Total operating hours	2803	n/a	n/a
HEGS input energy (MWh/yr)	589	n/a	n/a
Contribution to energy input (%)	11	n/a	n/a
Combined HEGS + FC			
Input energy (MWh/yr)	690	751	8.8
Contribution to energy input (%)	13	14	1
WECS			
Total operating hours	8164		
WECS input energy (MWh/yr)	4721		
Contribution to energy input (%)	87	86	-1
Mass Balance			
Fuel cell (Nm^3/yr)	65746	525839	
FC value (kWh/Nm3)	1.54	1.43	
FC&HEGS value (kWh/Nm3)	1.17	n/a	

Table X.X: Comparison of system design and performance parameters for Systems 1 & 3, 200 kW load and 40% EIL.

	200/40	200/10	Compare systems: 200/10 to 200/40
Electrolyser			
% time at idle / off	35	29	-6
% time at 90-100% load	57	63	6
Total operating hours	8760	8760	0
Consumption of system load (%)	52	27	
Fuel Cell			
% time at idle / off	89	90	1
% time at 90-100% load	0	0	0
Total operating hours	8760	8760	0
Contribution to input energy (%)	2	1	
HEGS			
% time at idle / off	69	76	7
% time at 90-100% load	17	12	-5
Total operating hours	2803	2156	-647
Contribution to energy input (%)	11	5	
WECS			
Contribution to energy input (%)	87	94	
Total operating hours	8164		

Table X.X: Operating hours for components in System 3 - 200 kW load, 40% and 10% EIL

System 3					***System 1***	
Fuel Cell	200 kW 40% EL		200 kW 10% EL		200 kW 40% EL	
Power Range [%]	*Hours*	*%*	*Hours*	*%*	*Hours*	*%*
0-10	7813	89.2	7949	90.7	6212	70.9
10-20	124	1.4	60	0.7	225	2.6
20-30	122	1.4	105	1.2	256	2.9
30-40	194	2.2	114	1.3	292	3.3
40-50	235	2.7	139	1.6	550	6.3
50-60	197	2.2	141	1.6	596	6.8
60-70	75	0.9	127	1.4	629	7.2
70-80	0	0.0	69	0.8	0	0.0
80-90	0	0.0	46	0.5	0	0.0
90-100	0	0.0	10	0.1	0	0.0
Total	8760	100	8760	100.0	8760	100

Table X.X: Operating hours for fuel cell components in Systems 3 and 1 - 200 kW load, 40% and 10% EIL

Experiments with the *practical* load profile:

2.4.2 Operating System 3 (FC + HEGS) as an energy independent facility with comparison of practical loads and electrolyzer characteristics

Part 1: System 3 with electrolyzer idle power rating of 40%

The component sizes of an optimised energy system suitable for meeting a 200 kW *practical* (electric-only) load at Mawson station using system 3 (FC and HEGS), and a conventional electrolyser with idling power (EIL) of 40% are detailed in Table X.X above.

The system includes an electrolyser with a rated power of 356 kW. This device subsequently has a rated energy demand that is almost 80% larger than the basic user load of 200 kW. This electrolyser operates consistently throughout the year and consumes 52% of the energy generated by the wind-H2 system. 35% of the annual operating hours are spent at idle (40% rated power) during periods of insufficient excess wind energy or full hydrogen storage. The electrolyser also spends 57% of the annual operating hours producing hydrogen at 90-100% capacity; indicating appropriate sizing of the electrolyser for the application. Although the electrolyser consumes a relatively high proportion of the total system energy input, the system also produces an energy excess of 1305 MWh/year. This represents 25% of the total power generation, is closely comparable with the user load, and is available fairly consistently throughout the year. Refer to Figure X below for details for electrolyser power consumption and excess power availability.

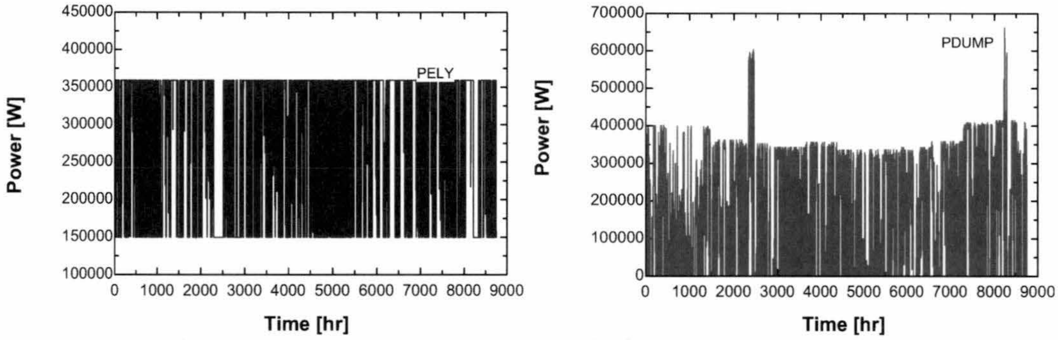


Figure X.X: electrolyser power consumption (left) and excess power availability (right) for System 3, 200 kW, 40% EIL

The system uses a physical storage volume of 375 cubic meters, equivalent to 375 000 water litres, to store approximately 60 000 Normal cubic meters of hydrogen. The physical size of this hydrogen system compares well with the current requirement to store 500 000 to 1 000 000 litres of diesel fuel at the station. The hydrogen storage volume also compares well with the reference diesel system for the model which stipulates 435 668 L diesel/year.

The capacity of the storage system is fully utilised, with the relative capacity ranging from 0.1-1.0 through the year (refer to Figure X.X below). This indicates that the system is well sized to meet the electrolyser production capacity, availability of excess wind energy, and hydrogen consumption to meet parasitic and user loads in the system. Two periods occur when the system effectively reaches full capacity at approximately 2400 and 8250 hours through the year, and a smaller peak also occurs at 5000 hours. At the first peak, the system is truly filled and results in a negligible amount of hydrogen dumping (1997 Nm^3).

This peak occurs just after a peak in wind power generation and at a period of moderate user load. The two other peaks also occur after periods of high wind power generation. The hydrogen storage levels decline when wind power production drops and/or the user load increases. The lowest storage level occurs at approximately 5500 hours, after the winter peak of user load but during a period of lower wind power production. At this lowest point, the storage capacity closely approaches the minimum storage below which the fuel cell stops consuming hydrogen (10% SOC). However, the system is effectively sized so that no demand for imported energy results although the remaining 10% of the hydrogen storage capacity provides an effective safety net for real world operations.

The storage SOC is balanced over the year, with the end of year SOC comparable or slightly higher than the initial SOC of 60%. This further confirms the sizing of the electrolyser and storage capacity. One minor point of concern for the system is the relatively small system deficit of hydrogen production (1.42%) that occurs over the year even though the annual SOC is balanced, as identified through post-optimisation analysis. This deficit could be addressed by increasing the electrolyser capacity slightly (perhaps by 2%) to increase the net hydrogen production. The availability of excess energy in the system makes this possible. The storage capacity would also need to be increased slightly to capture the hydrogen currently dumped during the first quarter of the year and to store the increased production from the electrolyser. However, an alternative approach would be to reduce the size of the FC or HEGS to reduce hydrogen consumption.

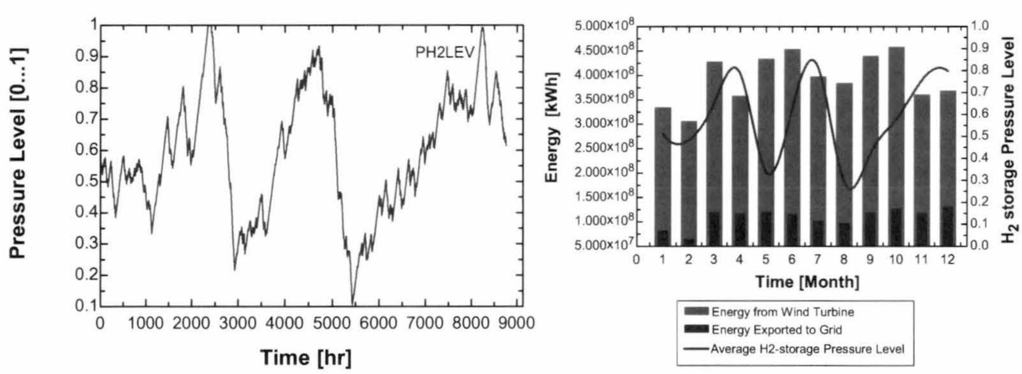


Figure X.X: electrolyser power consumption (left) and excess power availability (right) for System 3, 200 kW, 40% EIL

The system requires a hydrogen-fuelled power generation capability of 425 kW (rated power), which is met using a fuel cell (35%) and a HEGS (65%). The HEGS operates consistently throughout the year, contributing 11% to the total power output. The fuel cell operation is centred around the winter season (mid-year), is less consistent than then HEGS and contributes only 2% to the total system input (even though it is 35% of the HEGS size) (refer to Figure X.X below). Post-optimisation analysis indicates that the HEGS and FC components are slightly oversized, with the real generating capabilities of these components (combined) exceeding the minimum required by approximately 12% (Table X.X). Analysis of the FC chart below indicates that the 150 kW device is only operating to approximately 105 kW at peak power output, suggesting that it has approximately 30% over-capacity. Given that the FC contributes only one third of the total generation capability, this over-capacity is likely to be the cause of the total over-capacity. As the fuel cell operation accounts for 11% of hydrogen consumed in the system, a 30% reduction in the fuel cell capacity would reduce the hydrogen consumed by the component by a comparable amount, thereby addressing the total hydrogen production deficit of 1.4% discussed above.

This analysis that the specified fuel cell size is approximately 30% over-capacity is also supported through more detailed analysis of the operating hours of the component relative to the power range of the fuel cell (refer to Table X.X above). In this system, the FC exhibits zero hours of operation in the 70-100% power range.

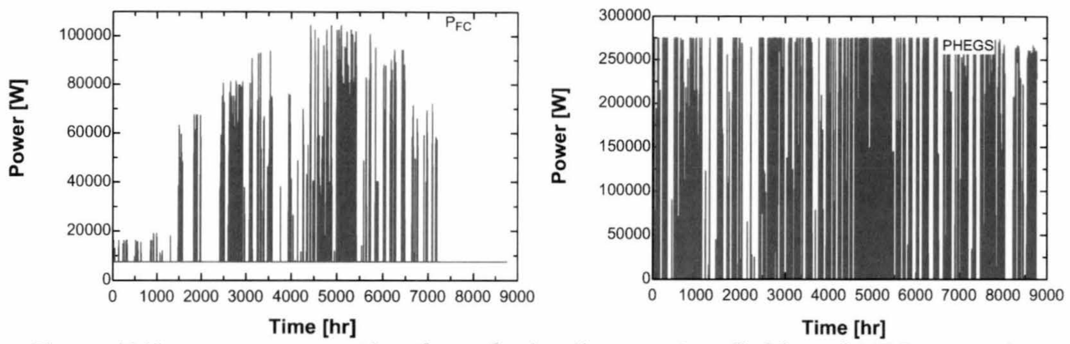


Figure X.X: power generation from fuel cell operation (left) and HEG operation (right) for System 3, 200 kW, 40% EIL

The broad proportions of power generation capacity of the FC and HEGS components were selected by the user after consideration of the relative advantages and disadvantages of the two technologies. HEGS components were seen to offer advantages of lower component capital cost (per kW capacity), longer and better known service lives, and greater availability of support infrastructure based on their use of conventional technologies. In contrast, fuel cells are currently significantly more expensive for comparable power outputs, have much shorter and less proven service lives, and are innovative technologies that do not have pervasive support infrastructure. On these principles, it would be preferable to operate the entire Mawson hydrogen system using HEGS technologies; however, the improved energy conversion efficiency and potential servicing advantages of fuel cells over HEGS indicates that they will play valid roles in operations in the future. A fuel cell is subsequently used in this system to provide approximately one third of the system power demands, with operation initiated when the system load exceeds the generation capacity of the wind turbines and HEGS. This strategy enables the system to use the HEGS advantages to full effect with the component operating consistently throughout the year. The efficiency advantages of the fuel cell are utilised for the upper third of generation capacity, thereby minimising the operating life of this expensive component.

Post-simulation analysis of the power generation and fuel consumption of these components indicates that the fuel cell has a higher hydrogen conversion efficiency when compared to the HEGS (1.54 / 1.14 kWh/Nm^3 FC/HEGS). This occurs even though the FC has approximately triple the operating hours of the HEGS, with 89% of operating hours spend at idle. In contrast, the HEGS duty cycle is more tailored towards using hydrogen fuel to generate useful power, with the device spending 69% of the year at idle/off (no H2 consumption), and 17% of the year (approximately half the hours of operation) in the 90-100% power range. Although the fuel cell duty cycle is much less tailored to maximise the use of hydrogen for power generation due to its role in meeting the upper third of station load and need for fuel consumption during idling, the inherent efficiency advantages of the fuel cell enable it to operate with a net efficiency advantage to the HEGS system. This efficiency advantage is the primary reason why fuel cell technologies are attractive for use in such applications – although they are more expensive components, they can enable reductions in the size of other components such as electrolyser and hydrogen storage. Therefore, increased investment in FC technologies could deliver reduced total capital costs for a system.

As an alternative, the system could be designed to make maximum use of the efficiency advantages of the fuel cell by using as it as the first response to deficiencies in the wind energy, thereby exchanging roles with the HEGS system. This would reduce the amount of time spent by the fuel cell at idle (less wasted hydrogen consumption) and improve the efficiency of hydrogen use for power generation through the use of a more efficient device. The capital investment in the FC would be maximised, and the less expensive HEGS component could be used to meet the lower duty cycle of the upper third of the load profile. This would also maximise the use of a component that can be switched off when not required, and minimise the use of hydrogen through the less efficient device. The current capital costs and/or the service lives of fuel cell components would need to be improved to make this alternative system a viable option, otherwise the increase in effective use of the fuel cell could reduce its service life to impractical levels. For example, if a PEM FC with a service life of 3000 hours were used to replace the HEGS component in System 3, the period of operation at power demands above idle would increase from ≈10% to ≈30% of the year (876 hours up to 2628 hours) using figures from Table X.X above. The actual in-service life of the component would therefore be reduced from 3.4 years down to 1.15 years. If the fuel cell stacks could be rapidly exchanged with new units, such as by using a modular stack system (proposed by a number of PEM FC suppliers), and the stacks were relatively cheap, the operating cost of the FC may be reasonable to user communities. However, if the stacks remain relatively expensive compared to HEGS components and are not easily replaced or serviced, they will continue to be better suited as secondary load servicing units in the immediate future.

This analysis has proven that a wind-hydrogen system can be successfully used to meet the electrical energy demands of Mawson station under the conditions specified. The analysis also indicates the relative advantages of different components for hydrogen fuel conversion to electricity (FC and HEGS). Detailed evaluation of the economic implications of using these different technology combinations would be advantageous to user communities and system designers in identifying the relative capacities and roles of the different components. Tools to enable such evaluation are being developed by Ulleberg and other collaborators (Houstein, 2005) for later inclusion in the modelling system toolbox.

Impact of load changes on system:

A **decrease of the station load by 10% to 180 kW** enabled reductions in the sizes of the hydrogen energy system components, including electrolyser size (17%), total generation capacity (11%) and storage capacity (17%). These values suggest a magnifying impact of the load change on changes in the electrolyser and storage component sizes (1.7X), and a dependent relationship between the two components. Post-simulation analysis indicates that the generation capacity for this system remains over-sized (14.5%), an increase over the reference (200 kW) system. This could be attributed to the 9.1% reduction in HEGS capacity, and continued over-sizing of the fuel cell (only 16.7% less than the reference system, which was determined to be approximately 30% over-sized).

If the fuel cell sizing in the 200 kW load reference system is assumed to be over-sized by 30% and is adjusted accordingly, as detailed in Table X.X following, the system exhibits only 0.3% theoretical over-sizing. Applying the same 30% reduction in fuel cell size for the system designed for the 180 kW load, the system exhibits only a 4.1% over-sizing. Changes in the electrolyser and storage capacity remain constant, but the total generation capacity is reduced by 10% - highly comparable with the change in system load. This change is shared approximately equally between the fuel cell and HEGS components.

A **10% increase to the maximum station load to 220 kW** increased the hydrogen energy system component size requirements, including electrolyser size (28%), total generation capacity (19%) and storage storage (31%). These figures again suggest a correlation between the electrolyser and storage sizes, and a magnifying impact of the change in load on all component sizes.
The fuel cell generation capacity increased by 37%, significantly more than the increase in load. At this level, the component contributes 40% of the total generation capability of the hydrogen system, explaining the disproportionate increase in total generation capacity (19%).

The concept that the fuel cell component may be 30%+ over-sized, as validated by the continuing 12.4% total generation over-capacity for the 220 kW user load system, was tested by re-calculating the relative system sizes with a 30% reduced fuel cell size in the 200 kW and 220 kW systems. This data is presented if Table X.X below. A revised FC rating of 143 kW (70%) generates a revised total generation capacity increase of 18% and a theoretical system under-capacity of 0.2%. This is achieved via a 44% increase in FC capacity and 9% increase in HEGS. Further analysis of these figures becomes difficult as part of the increased generation capacity is required to meet the parasitic energy demands of the much larger electrolyser; however, the disproportionate increase in electrolyser size must be partly attributed to the over-sized fuel cell component used within the model and the subsequently excessive hydrogen consumption from this device (particularly during idling). Any assumption that the fuel cell capacity can be reduced should extend to a reduced capacity for the electrolyser. The value of such a reduction would be dependent on the proportional contribution of the fuel cell to generation capability and the total amount of hydrogen utilised by the component, but would be much smaller than the proposed 30% reduction in fuel cell size.

Efforts to execute simulations of the energy system with the reduced fuel cell rated power were unsuccessful. This outcome indicated that some conflicts could occur in the model algorithms for specific configurations of energy system components and user load.

Elyzer idling power (%) (rel to rated power)	40 corre	40 mod	Compare corrected to model (% Δ)	40 corre	Load compare to 200 (% Δ)	40 mod	Load compare to 200 (% Δ)	Compare corrected to model (% Δ)	40 corre	Load compare to 200 (% Δ)	40 mod	Load comparis to 200 (% Δ)	Compare corrected to model (% Δ)
Component specs													
Peak load (kW)	**200**	**200**	0 0	**180**	-10	**180**	-10 0	0 0	**220**	10	**220**	10 0	0 0
Elyzer rated power (kW)	356	356	0 0	295	-17 1	295	-17 1	0 0	455	28	455	27 8	0 0
FC rated power (kW)	100	150	-33 3	87 5	-12 5	125	-16 7	-30 0	144	44	205	36 7	-30 0
HEGS rated power (kW)	275	275	0 0	250	-9 1	250	-9 1	0 0	300	9	300	9 1	0 0
Total gen capacity (kW)	375	425	-11 8	338	-10 0	375	-11 8	-10 0	444	18	505	18 8	-12 2
H2 storage vol (m^3)	375	375	0 0	310	-17 3	310	-17 3	0 0	490	31	490	30 7	0 0
Component evaluation													
MIN gen need (kW)	361	361	0 0	313	-13 2	313	-13 2	0 0	426	18	426	17 9	0 0
MAX gen need (kW)	602	602	0 0	513	-14 8	513	-14 8	0 0	734	22	734	21 9	0 0
REAL H2 gen cap (kW)	362	406	-10 7	326	-9 9	359	-11 5	-9 1	425	17	478	18 0	-11 2
REAL vs MIN (%)	0 3	12 4		4 1	3 8	14.5	2 1		-0 2	-0 5	12 4	0 0	

Note: '40 corrected' data presented for system 3, 40% EIL with FC rated power reduced by 30%.

Table X.X: Component size data for System 3, with comparison of model data and corrected model data for 40% EIL design.

Appendix 3. Further analysis of wind speed data from Mawson station

Further analysis of wind speed data presented in this Appendix:

1. impact of extrapolation of historic data from 3 hourly data and potential loss of gusty peaks.
2. occurrence of wind peaks coincident with evening heating loads.
3. comparison of compiled 2003 dataset with 44 year dataset
4. comparison of measurement times.
5. comparison of measurement method.

3.1 impact of data extrapolation on peaks

Need to consider history of data preparation ... 2003 data set was generated from 10 minute data so very high resolution capturing all small peaks, while the 44 year data set was extrapolated from 3 hourly data where any short time step peaks (gusts) were lost. Consequently the MAX and MIN ranges presented by the historic data do not include such short-term gusts.

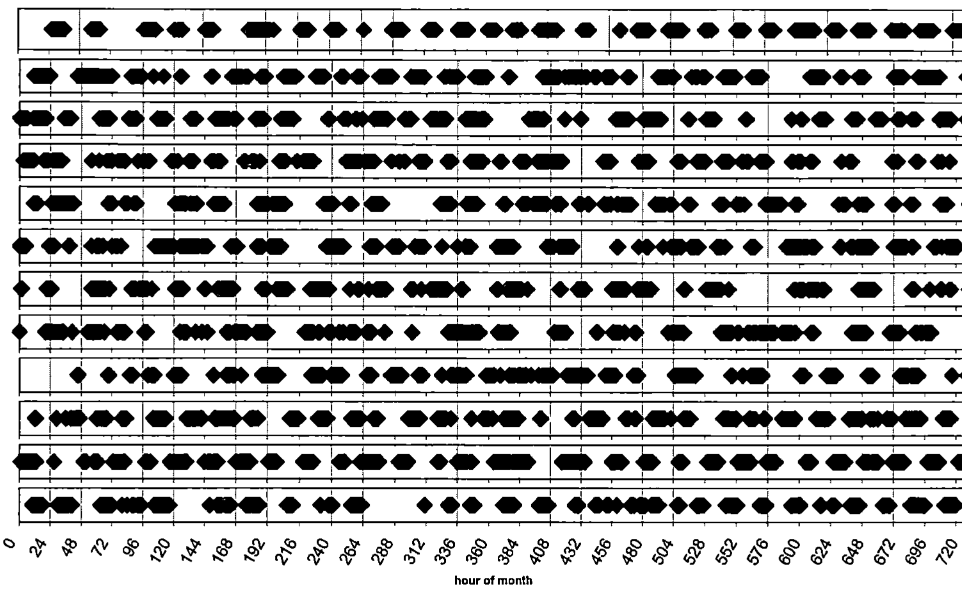
Time period 2800 – 3000, for example, is 200 hours, less than 10 days, hence suggests a period of a few days when winds were lower than usual. Even though 44 year data is only 3 hourly, is capable of capturing periods of longer time when wind speed is low (eg. 5 days of bad winds). Need to consider the potential impact of extrapolating the 10m data to 30m for the 44 years – as shown in the 10m vs 30m comparison for 2003, much greater variation between average and max/min values at 30m due to reduced impacts from ground friction. Therefore, is conceivable that true wind speed measurements at 30m for the 44 years would have more peaks.

In summary, the extrapolated 44 year data has two primary sources of error that must be considered:

1. time-based extrapolation from 3hourly down to hourly will reduce the impact of possible peaks that occur in shorter time periods, in contrast, the 2003 data set is assembled from 10sec data so can capture all such peaks. These impacts become less important when looking at longer term trends.
2. Extrapolation from a 10m measurement height to 30m height using a correction factor that was derived from the 2003 data set.

3.2 Wind peak occurrence at midnight

Analysis of wind speed peak occurrence at midnight



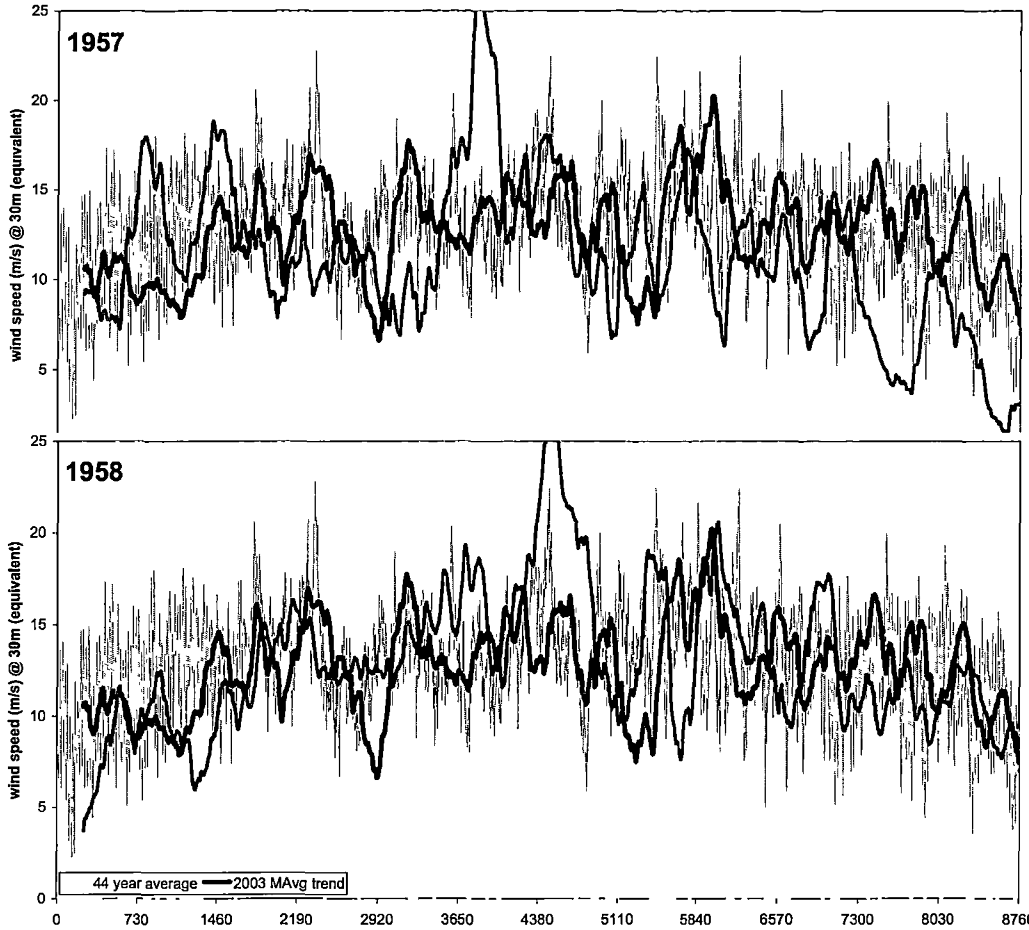
This graph examines the time based occurrence of peaks in the local timed wind data for 2003. Peaks are identified as wind speeds within 30% of the maximum wind speed measured over a 24 hour period. Zero and 24 hour time steps represent midnight. The data illustrates that wind peaks generally occur at night. Analysis of data indicates that 265 (72%) nights have wind peaks during 10pm-3am for 2003.

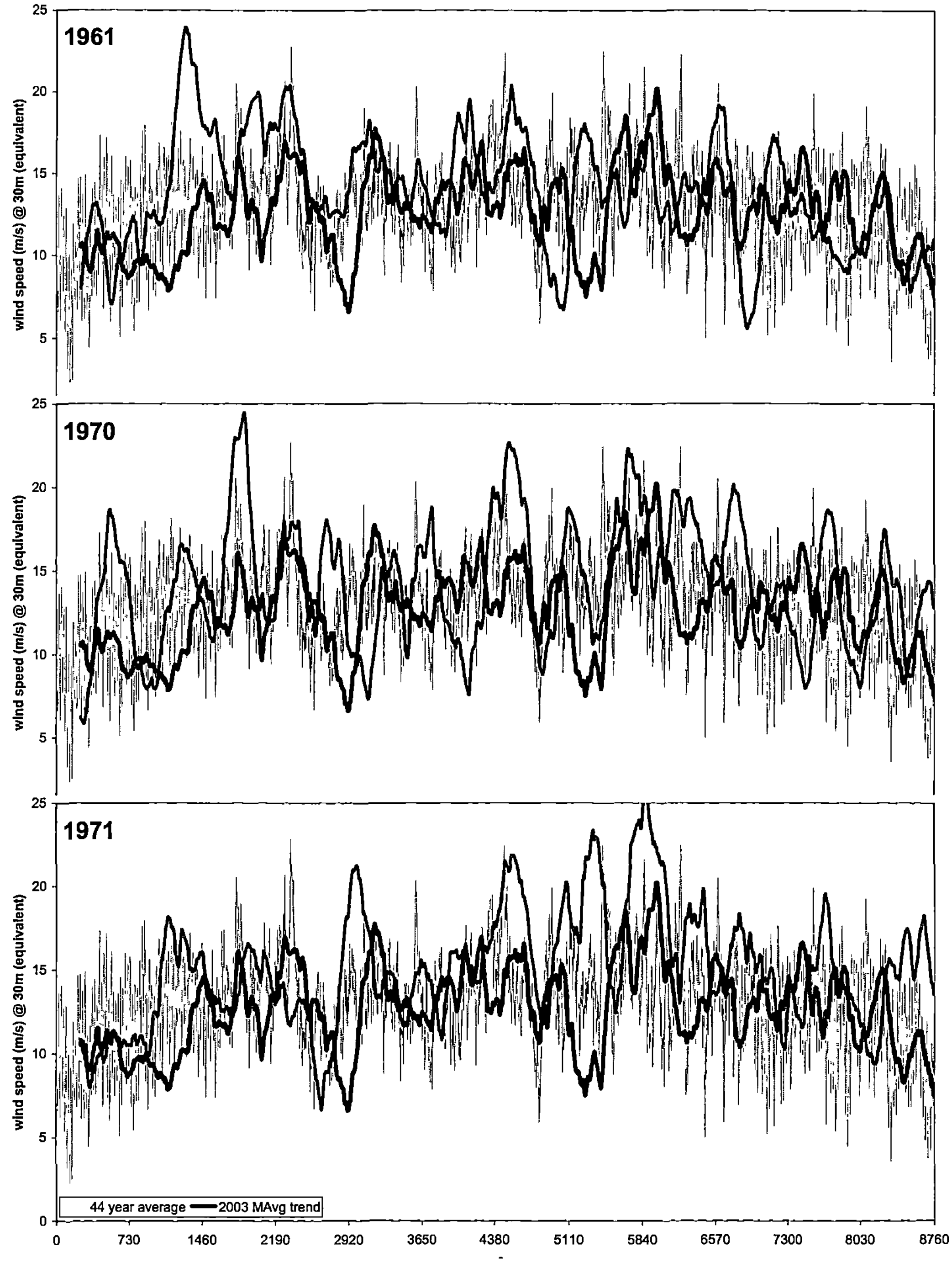
3.3 Comparison of compiled 2003 dataset with 44 year dataset

Analysis of the similarity between the 2003 dataset (moving average) and eleven different kinds of years from the 44 year dataset, including a reasonably average year.

1957	generally low, and very low at end of year
1958	start lowest, single winter peak (in middle of range), low end of year
1961	peak early in the year then decays for rest of year
1970	generally high and flat - average high year
1971	hight, single winter peak of 19m/s (maximum)
1982	generally poor year, mid year slump (not peak) but overall quite flat
1983	Mid year trough but peaks either side, four inflections
1991	generally high and flat - average high year
1993	flat and low
1997	flat and mid
1998	average throughout year, except for having 5 inflections, very low at end of year

The results indicate that the 2003 dataset is highly comparable with the years considered in terms of variability, general behaviour and maximum and minimum wind speeds.


1957
1958
wind speed (m/s) @ 30m (equivalent)
44 year average
2003 MAvg trend
0
5
10
15
20
25
730
1460
2190
2920
3650
4380
5110
5840
6570
7300
8030
8760



1961
1970
1971
wind speed (m/s) @ 30m (equivalent)
25
20
15
10
5
0
44 year average
2003 MAvg trend
0
730
1460
2190
2920
3650
4380
5110
5840
6570
7300
8030
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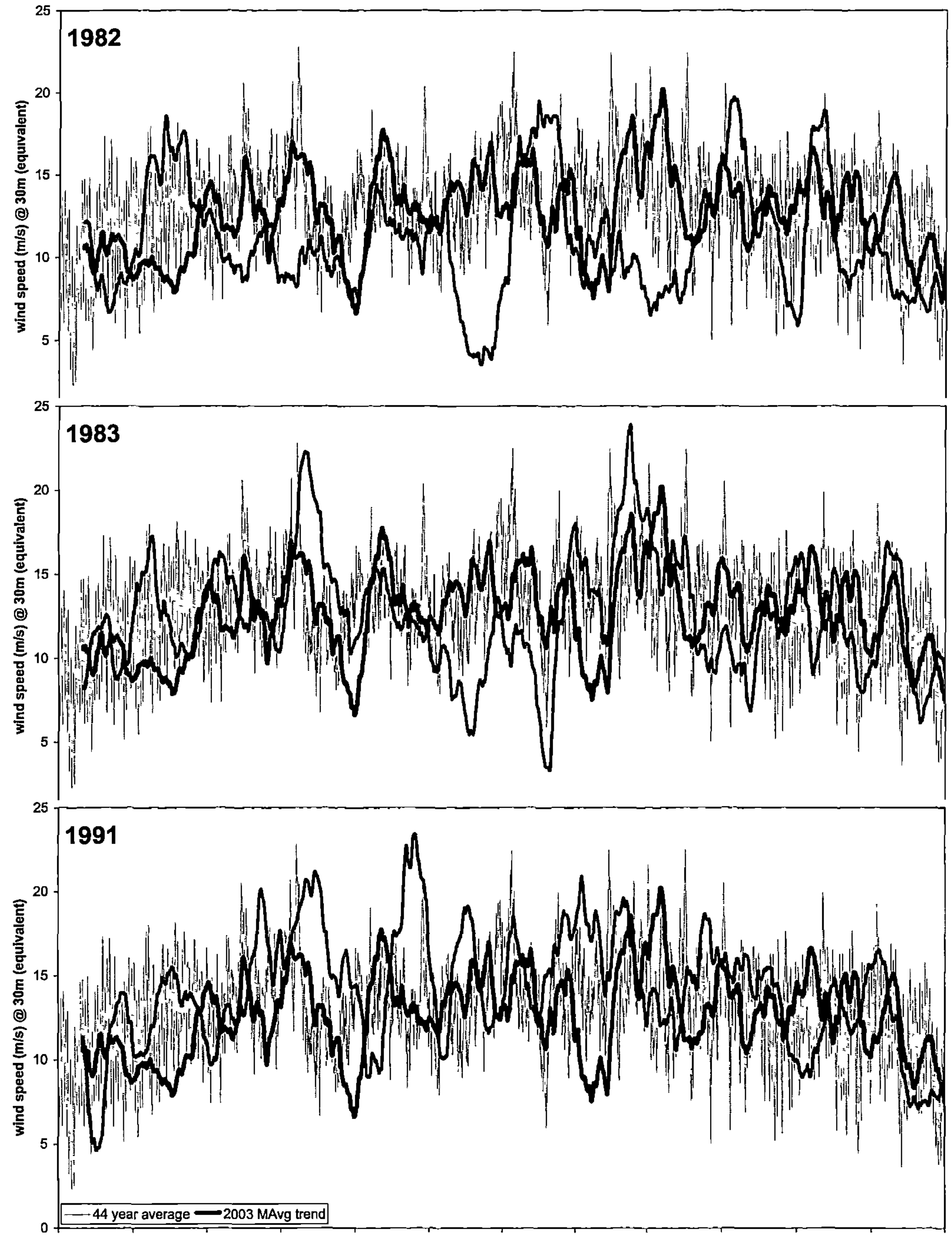
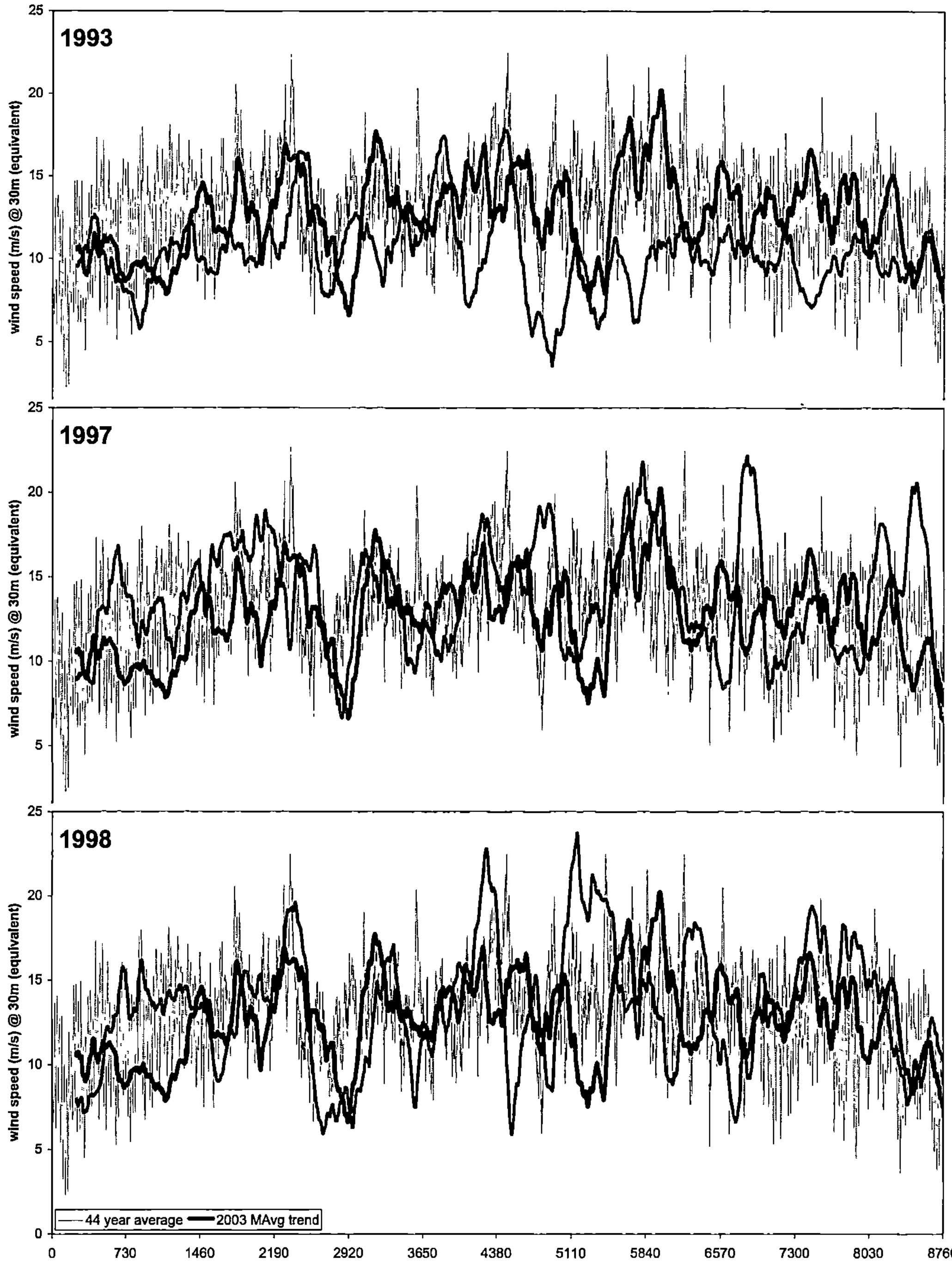

1982
1983
1991
wind speed (m/s) @ 30m (equivalent)
25
20
15
10
5
0
44 year average
2003 MAvg trend
0
730
1460
2190
2920
3650
4380
5110
5840
6570
7300
8030
8760


1993
1997
1998
wind speed (m/s) @ 30m (equivalent)
44 year average
2003 MAvg trend
0
5
10
15
20
25
730
1460
2190
2920
3650
4380
5110
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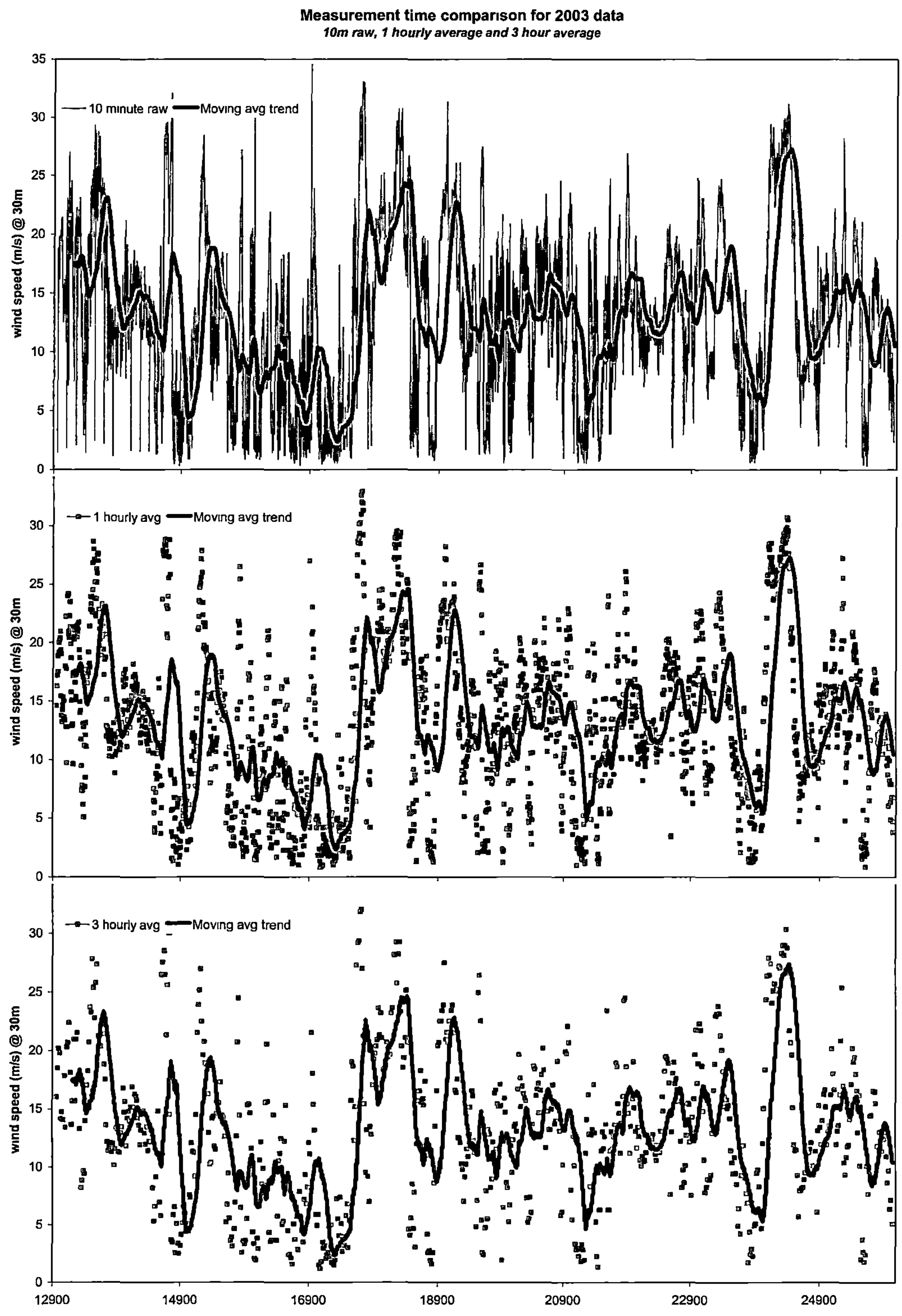
6570
7300
8030
8760

3.4 Comparison of measurement times

10min, 1 hourly average, 3 hourly average (for 3 month period)

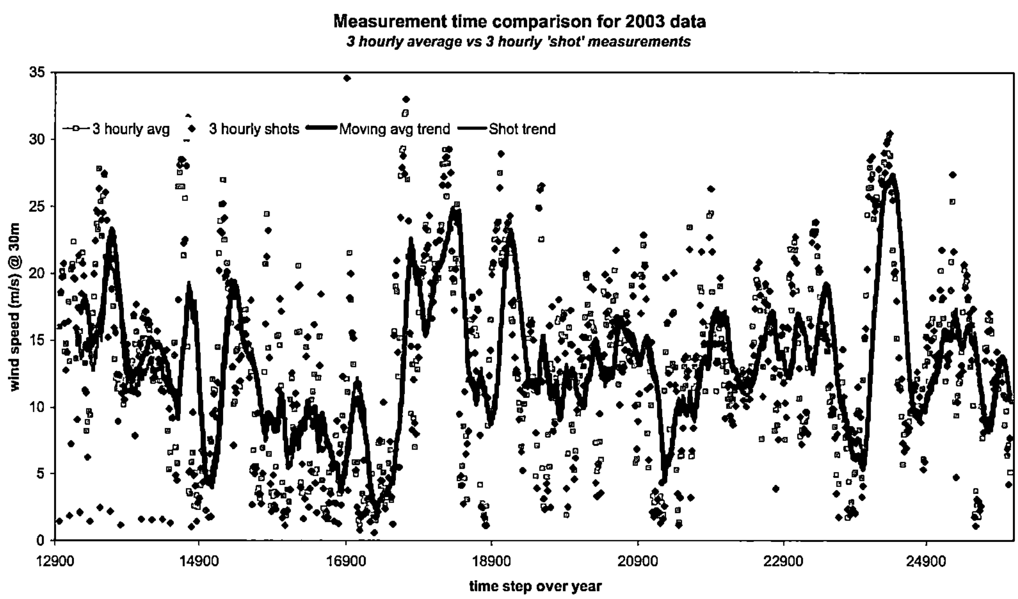


Examines variations in the data density and corresponding moving average trend lines (250 data points) of three different resolutions of time measurement.

Outcome: the trends lines of the three different time series are highly consistent, indicating that the use of lower resolution data (3 hourly averages) does not remove broad trends.

3.5 Comparison of measurement method

3 hourly averages of 10 minute data, or 3 hourly 'shots' (3 month comparison)



Enables comparison of the trends in three hour data sets when the data is captured as a three-hourly 'single shot' sample of the wind speed, or calculated as an average of ten minute data. Illustrates that the short-term trends within the two data sets are closely comparable. This is important to determine if the hourly data sets that were produced for the 44 years of historic data from 3 hourly data sets will have less detail than the 2003 data (as produced for hourly reading from 10 minute data). This comparison of 3 hour constructions shows that the general trends are still clearly present, so a better situation can be assumed for the hourly data.

Appendix 4. A work sheet for undertaking HYDROGEMS modeling work

David Pointing
11 Nov 2003

There are a number of possible approaches to modeling energy systems:

1. Existing integration - developing a model of an existing system and activity to determine how hydrogen energy technologies may integrate to enhance the operational, economic or environmental performance. Such a system is defined by the current infrastructure and known patterns of use, but provides opportunities to enhance performance and create change.
2. New system - developing a model of an energy supply system that is designed to support a new system and activity, subsequently free from the constraints of an existing system and one which allows an optimized and modernized system to be developed.

In both circumstances, full details of the activity and actual (or anticipated) energy demands and consumption profiles must be determined.

Key steps in the development of hydrogen energy models for energy supply systems

Part 1: Developing the background profile

1. Define the scenario - define and constrain the energy use scenario to gain a solid understanding of the community, activity, local environment and available resources that you are attempting to model. The energy use scenario, and subsequent operation model, will consider elements that are far more complicated than the simple technical performance of the system.
2. Define overall performance indicators and constraints for the energy supply system – define what is sought from the energy supply system, and what elements may restrict the methods and performance of the system. Constraint may include the use of an existing energy supply infrastructure, environmental impact restrictions, capital or life-cycle costs or community or operational factors.
3. Define the key energy consumption sub-systems – eg. Stationary electrical, low-voltage and high voltage, specific equipment items, space heating, water heating, vehicle fuelling, remote equipment power support etc.
4. Define key technical elements – examples may include the use of specific local energy resources (wind, solar, natural gas), the inclusion of key technologies (perhaps for demonstration purposes), or the use of existing infrastructure.

Part 2: Key Scenario Data Collection

5. Define the key energy demand parameters and use profiles – specify with as much detail as possible what activities will be supported, identify the power demand requirements for these activities and critical components, and subsequently the periods of operation, the flexibility of operating times etc.
6. Define the technical elements of stipulated technologies – collect all necessary technical details to accurately define any specifically stipulated technology

components required in the energy generation and distribution system – eg: existing components of infrastructure or elements that are to be demonstrated.

7. Collect all necessary data files for external factors that will influence the performance or selection of energy supply system components – eg: weather data, including wind and solar resources, fuel costs, operating costs, environmental data (temperatures, terrain). If the required data is not directly available, identify sources for correlation or initiate action to develop synthetic data files or acquire real data at the field site.

Part 3: Initial energy supply system selection and evaluation – technology focus

1. Initial Design Modelling – apply low-resolution modeling tools such as HOMER or ViPOR to undertake early selection and evaluation of potential energy supply system designs. The demand for and complexity of such evaluations will depend on the scale and complexity of the energy use scenario, and on the restrictions to technologies potentially available.
2. Select a short-list of high potential energy supply system designs for optimization. Selection should be based on the outcomes of the technical assessment models and general consideration of the other performance requirements and constraints for the energy use scenario.

Part 4: Initial energy supply system selection and evaluation – non-technical focus

1. Conduct a detailed evaluation of the performance of the technically leading energy supply system designs against the specified constraints and performance requirements of the energy use scenario. This selection may consider quasi-technical factors such as life-cycle and capital costs, or non-technical factors such as impact on the community (change management), environmental impacts, maintenance capability, flexibility, support requirements, safety etc. Pointing's (2001) evaluation method is one possible example.

Part 5: Selection of short-list of energy supply system design(s)

1. The outcomes from Parts 3 & 4 should be applied to select a short-list of energy supply systems that perform well w.r.t. the technical and non-technical demands of the scenario. This short list may contain one to several potential systems. The list contents will be used in subsequent design optimization processes and selection of a final system design.
2. A balance between focused evaluation of a single design and the additional burden of evaluating multiple designs must be considered. The following processes apply to a single system design, and may be repeated on the other candidates in the short-list.

Part 6: Optimisation of energy supply system design

1. Detailed technical modeling – utilise detailed technical modeling tools to create a comprehensive model of the short-listed energy supply system design, including the complete technical details of any specific components pre-selected for inclusion in the energy supply system. Use the modeling software to optimize the system design to meet the performance requirements and scenario objectives. Modelling packages such as HYDROGEMS are suitable for this.

Appendix 5

Application for research to the Human Research Ethics Committee (Tasmania) Network for the project:
"*Interviews to identify current attitudes towards hydrogen energy use in Antarctica and other regions of Australia*"
(8 pages)

Tasmania
DEPARTMENT *of* HEALTH *and* HUMAN SERVICES

Human Research Ethics Committee (Tasmania) Network

UNIVERSITY OF TASMANIA

Office Use Only:
Date Submitted: **Project Reference No:**

APPLICATION FOR RESEARCH INVOLVING HUMAN SUBJECTS

On completion please return to: Executive Officer
Research and Development Office
GPO Box 252-01
Hobart, Tasmania 7001 Australia

GRANT APPLICATION

TITLE of Investigation

Interviews to identify current attitudes towards hydrogen energy use in Antarctica and other regions of Australia.

A. OUTLINE OF PROPOSAL
Applicants

Title/Name	Position	School or Discipline
Chief Investigator/Supervisor		
Dr Kelvin Michael	Senior Lecturer (PhD supervisor)	IASOS
'Phone **6226 2977** Fax 6226 2793 Email Kelvin.Michael@utas.edu.au		
Other Investigator(s) / Students		
Mr David Pointing	PhD student	IASOS
'Phone 6226 1752 Fax 6226 2973 Email dsp@utas.edu.au		
Other Investigator(s) / Students		
Dr Julia Jabour	Lecturer	IASOS
'Phone 6226 2978 Fax 6226 2973 Email Julia.Green@utas.edu.au		

Purpose

Research

Aims

The objective of the study is to identify via personal surveys and interviews the existing perceptions within the Australian Antarctic research (and support) community towards the use of renewable hydrogen energy technologies in the Australian Antarctic Program (AAP). Specific emphasis will be placed on identifying the perceived problems with hydrogen energy technologies (barriers to use) and the perceived opportunities that the technologies could offer (driving forces for use). The study will also seek to identify how other applications and communities have dealt with the issues surrounding community acceptance of hydrogen energy technologies – focusing particularly on communities that have more experience and progress in the implementation of hydrogen technologies. These alternative environments and applications will provide a broader perspective of the barriers and drivers that the implementation of hydrogen energy technologies faces, and will provide an indication of the implementation issues that may emerge if hydrogen energy technologies are to be implemented an Antarctic operations.

Justification

Global climate change and environmental impacts that result from human activities are an important issue for the world community, and efforts to reduce these impacts will require technological and social/behavioural change in all aspects of society. With respect to the impacts that are a consequence of meeting global energy needs, hydrogen energy technologies are now broadly viewed within engineering and energy supply fields as offering considerable opportunities to improve the economic, environmental and operational performance of the energy supply systems used by society, including having the potential to replace fossil fuels as the future foundation of all energy systems. However, hydrogen energy technologies are not yet in common use around the world due to a number of reasons that are both technical and non-technical in nature. Many of the technical barriers are being overcome and the technical feasibility of the technology is being illustrated via public demonstrations. In order to advance the implementation of hydrogen energy into communities, the remaining non-technical barriers must be overcome. Examples of the non-technical barriers have been proposed to include limited understanding about the capability and value of hydrogen energy technologies, misconceptions about the operation, safety and feasibility of hydrogen energy technologies, and a lack of acceptance and support for this new energy supply technology within the intended user communities. Unfortunately the greatest focus on hydrogen energy technology development and implementation in the past has been on the technical issues, and only now are proponents for hydrogen energy systems examining the non-technical issues, such as community acceptance, that must be overcome before hydrogen energy technologies will effectively penetrate communities and their benefits can be accessed.

The Australian Antarctic research community, which operates in the harsh and pristine Antarctic environment, has a strong focus on pursuing activities with minimal impacts on the environment, and hydrogen energy technologies can assist in achieving this ambition. Initial technical assessments have indicated that hydrogen energy technologies can play a valuable role in Australia's Antarctic operations, but the target community (Antarctic researchers and support personnel) will need to be educated and informed about the new technology, and a long-term strategy developed to facilitate the safe, effective and timely implementation of hydrogen energy technologies. A significant technical (demonstration) project is now being developed to install a demonstration wind-hydrogen energy system at Mawson station in Antarctica which will have a significant impact on the perceptions of the Australian Antarctic community towards hydrogen energy use. However, the demonstration project does not formally include review of the impact that the demonstration will have on the Antarctic community towards such technologies.

The study is therefore important as it will identify and evaluate the existing level of understanding, support, and fears about hydrogen energy technologies within the Australian Antarctic community - before they are altered by the Mawson demonstration project, and will provide a baseline to evaluate the impact that the demonstration project will have on the Antarctic community's perceptions. The outcomes from the study will also be used to develop strategies and actions that will result in the effective implementation of an environmentally friendly energy supply system in Antarctica, with potential for the associated experiences to be transferred to implementation programs for other communities and environments.

Period of investigation

Commencement date:	February 2004	Completion date:	February 2005

Funding

Source/potential source of funding and amount:

Under the National Statement (2.21) a researcher must disclose (i) the amount and sources or potential sources of funding for the research; (ii) any affiliation or financial interest. In some cases there may be a risk that potential subjects will be coerced or induced to participate.

Do the investigators have any financial interest in this project? No

Funding Bodies: University of Tasmania PhD scholarship, and Tasmanian Government Economic Development department (Antarctic Tasmania office) research grant for PhD support, shared over 3 years.	Amounts over 3 years. Utas: $54 K (approx). AntTas: $60 K (approx).

Approval from other Ethics Committees or Institutions
If this project has been approved by any other Ethics Committee or Institution, please provide evidence of this approval.

Has this protocol **previously** been submitted to the Southern Tasmania Social Sciences Human Research Ethics Committee? If **'yes'** please indicate when and the reference. Yes No ☑

Does this project need the approval of any other Ethics Committee? If 'YES', Please indicate below what Institutions are involved and what the status of the Approval? Yes No ☑

Other Ethics Committees: Status:

Relevant references
List the most relevant and current references (a) by the investigator; (b) by others:

Pointing, D., Michael, K., and, Magill, P. (2003) "*Developing an Implementation Strategy for the Antarctic Hydrogen Energy Economy*"; Paper presented at the Australian & New Zealand So Energy Society (ANZSES) conference, November 2003, Melbourne, VIC, Australia.

Pointing, D. (2002) "*Is Hydrogen Ready for Antarctica?*"; Paper presented at the Australian & New Zealand Solar Energy Society (ANZSES) conference, November 2002, Newcastle, NSW, Australia.

Pointing, D. (2001) "*Is Hydrogen Ready for Antarctica?*" Honours thesis submitted for B. Antarctic Studies degree, University of Tasmania, Institute of Antarctic & Southern Ocean Studies. Available on-line via: www.iasos.utas.edu.au/h2esa

Kemp, D. (2003) "*Hydrogen – New Energy Source for Antarctica*"; Media release by the Australian Minister for Environment and Heritage, Dr David Kemp, 20 May 2003, cited 1 Nov 2003, available on-line via: www.deh.gov.au/minister/env/2003/mr20may03.html

Steel, J.D. (1993) "*Alternative Energy Options for Antarctic Stations*"; Honours thesis submitted for B. Antarctic Studies degree, University of Tasmania, Institute of Antarctic & Southern Ocean Studies.

B. PROCEDURES

Detailed procedures

The project will undertake a series of interviews and surveys with representative figures in the Australian Antarctic research community to determine their views on hydrogen energy use in Antarctica. Interviews and surveys will also be conducted with other Australian and international parties who have associations with the implementation of hydrogen energy technologies in other applications and environments.

How will the interviews be undertaken?
The interviews will be conducted on a personal basis where possible, and via email or telephone correspondence as an alternative (identified as written surveys). The interviews and surveys will be undertaken one-to-one, and no multiple candidate surveys will be conducted. The interviews will generally be undertaken in the candidate's workplace unless another location is more convenient. The interviews are anticipated to run for approximately 30 minutes, and each candidate will be interviewed only a single time.

Who will be interviewed?
Approximately 40 candidates will be interviewed in total, capturing the perceptions of a range of influential parties within the Australian Antarctic research and support community, and allowing contrasts to be drawn with the experiences of other parties who are implementing hydrogen energy systems in alternate applications or environments. The interview candidates will represent three different influential groups that have been identified by the research team. Further details of the three groups are provided below.

What questions will be asked in the interviews and surveys?
Three different sets of interview questions will be developed, reflecting the different relationship or approach and the depth of knowledge of the three candidate groups towards energy use and hydrogen energy technologies specifically. The questions will generally focus on the themes:

- What is the candidate's understanding of hydrogen energy and the current and future capabilities of the technologies?
- Do they understand the reasons for hydrogen energy use in Antarctica?
- What do they perceive the barriers to implementation to be (in Antarctica or elsewhere)?
- What do they believe the driving forces for implementing hydrogen energy are?
- What actions does the candidate believe are required to advance the evaluation or implementation of hydrogen energy use in Antarctica?

Details of the interview questions are attached in the supporting documents.

How will the data from the interviews and surveys be recorded?
The personal interviews will be recorded on an audio tape recorder, and transcripts created after the interviews. Candidates interviewed in this manner will be sent a copy of the interview transcript after the interview for verification and for their records. Interview candidates who cannot be interviewed in person will be interviewed via telephone (again recorded) or sent the interview questions via email. The nature of the interview/survey questions may require a series of email surveys to be sent to each applicant.

How will the data from the interviews be evaluated and utilised?
The responses from the interviews will be transcribed and assessed to determine:

1. What is the current level of awareness and accuracy of knowledge/understanding of hydrogen energy technologies and their capability for use within the Australian Antarctic Program. This information will be used to determine if the subsequent responses from the candidates are based on factual information or if further education is required.
2. What are the perceived current barriers to and driving forces for hydrogen energy use in Australia's Antarctic Program as a complete list of all relevant Antarctic responses, and identification of the leading (most common) responses by the Australian Antarctic research community.
3. Are other projects involving the implementation of hydrogen energy technologies encountering similar or different issues to those faced or predicted by the Australian Antarctic community.

Where is this project to be conducted?

The project will be conducted at the University of Tasmania (Hobart campus), and via personal visits to interview candidates in Tasmania and other Australian and international locations where possible. When personal interviews are not viable, the project will be conducted via email or telephone correspondence.

SUBJECTS

Selection of subjects

Interview candidates will be selected by the project team from the Australian Antarctic research and support community, or from other projects of relevance in Australia and internationally.

Candidates or representative positions will be selected based on the research team's perception of the candidate's potential to influence the implementation and use of hydrogen energy technologies in Antarctica. Once identified, each potential interview candidate will be categorised relative to three specific candidate groups.

Details of the three groups are included below. Examples of proposed interview positions and/or individuals include the Director, Chief Scientist, and Chief Engineer of the Australian Antarctic Division (AAD), and field scientists within the Australian Antarctic Program.

The interview/survey candidates will form three separate groups, identified as:

1. Hydrogen energy technology implementers – this group will include people who are proponents for the technology or are working on the implementation issues related to different projects around Australia and internationally.
2. Implementation "targets" for hydrogen energy use in Antarctica – essentially people who represent the various facets of the Australian Antarctic research community and therefore represent the potential users (or support personnel) of hydrogen energy technologies used in Antarctica. This group will also include representative personnel in other Antarctic programs or equivalent organisations in the Arctic environment.
3. Energy supply and Operations Policy Makers – this group will include people who dictate or influence the formation of policy instruments that impact the operations and energy supply procedures undertaken in Antarctica and other environments.

Roughly equal numbers of candidates are sought within each of the three groups (10-15), and approximately forty (40) positions have been identified to date, as detailed in the supporting documentation. The number of interview candidates may grow as additional hydrogen energy implementation projects emerge on the Australian and international scene, which will provide further opportunities to capture knowledge and experience relating to hydrogen energy implementation.

The selection of the candidates is to be made by the study team on the basis of what positions within the AAP would influence the implementation of hydrogen energy technologies, and related knowledge of other hydrogen energy implementation programs around the world through which valuable knowledge may be captured.

Recruitment of subjects

The individuals selected for involvement will be personally contacted via letter or email to determine their interest and availability to participate in the study. The initial contact information will include details of the background, objectives and procedures of the study but will not include specific details of the interview questions. The initial contact information will also detail the confidentiality issues associated with the project and the time demands that will be placed on the candidates. The voluntary nature of the study will also be highlighted.

Details of the initial contact email for candidates is included in the supporting documentation.

As all the participants will be deliberately selected by the research team, all invitations to participate will be issued personally.

Information about subjects

1. State whether information will be identified, potentially identifiable or unidentified

Will the Information collected be:

De-Identified		*(not re-identifiable, anonymous)*
Re-Identifiable	☑	*(coded, re-identifiable)*
Identified	☑	*(data that allow the identification of specific individuals)*

If personal (identified or potentially identifiable) information will be collected in this study give details of the information that will be collected. Also indicate how the confidentiality and anonymity of the participants will be protected.

2. Will any personal information be collected from sources other than the subjects themselves?
(Refer: Privacy Legislation Section 95A - National Privacy Principles)

No.

3. **Will data on individual subjects be obtained from any Commonwealth Government agency without seeking the Consent of the Individuals? *(Refer: Privacy Legislation Section 95 Information Privacy Principles – Appendix 2 of National Statement)***

No.

Potential risks

1. Identification of the Risks:

No significant risks have been identified – the net level of risk is projected to be minimal.

2. Precautions taken to mitigate the risks:

Interview candidates will be fully informed of their rights to either withdraw from the interview process or elect not to answer specific interview questions. As the interview questions will not be intrusive in any way, this is perceived to be of little risk. Candidates will also be offered the opportunity to accept or refuse audiotaping of the interview, and their approval as well as approval of the post-interview transcripts will be sought. The candidates will be asked to specify how their interview responses may be used in the study.

Refer to the Project information form for specific details on the options offered to participants.

Post contact
Candidates who are interviewed in person or by telephone will be provided with a transcript of their verbal interview for verification and for their records. Email survey participants will receive confirmation of their survey response only (and thanks for participation). Candidates will also be contacted to confirm the use of any direct responses from the interviews in publications generated based on the outcomes of the study.

Remuneration
No payments will be made to participants.

Confidentiality and anonymity (Please refer to the Code of Conduct in Research available at the website: http://www.avcc.edu.au/news/public_statements/publications/glrespra.htm)

Confidentiality Confidentiality of information is protected when it is not disclosed or revealed to other persons by the investigators. Please answer the questions below in order to ensure this.

All raw data must be held on University of Tasmania Premises for a period of at least 5 years.

Interview records and processed responses will be kept within IASOS, stored in secure (locked) digital and physical systems. The data will be destroyed in an appropriate manner after 5 years.

Are Audiotapes being used to record data? Yes

If **YES** then please indicate how the anonymity of the participants is going to be protected:

Anonymity: Anonymity means that individual subjects are not identifiable. In some studies, eg many surveys and questionnaire-based studies, individual subjects' names are not recorded. In other studies identifying information is collected and measures must be taken to maximise the security of this information.

How will anonymity of subjects be assured?

As the interview process will be conducted using personal interviews, true anonymous responses are not possible in this study. However, the level of identification of the interview candidates within the published results can provide a level of anonymity where only candidate positions (not individuals) are identified and general responses (not direct quotes) are used to substantiate the study outcomes. If such anonymity is required by the candidates, it will be achieved by informing each candidate of the methodology and intended use of the interview responses prior to their participation. Candidates will requested to specify the level of use or exposure they approve for their responses, and any candidate that allows direct quotations will be sought to supply specific approval before each use. Unfortunately, for some candidates the direction correlation between an individual and their position will make anonymity impossible and such applicants may prefer to not participate. Their option to do so will be clearly identified.

All candidates will be also be informed that a list of the positions or roles of the interview candidates will be include in the study outcomes as such data is crucial to the outcomes of the study. The candidates can further permit the use of their names for quotation purposes.

Are Focus Groups involved in this project? No

Administration of substances/agents

None

Other ethical issues

None

Information sheet

Is the Information Attached? Yes

Consent form (Refer 1.7 - 1.12 National Statement)

Is the Consent Form Attached? Yes

C. DECLARATIONS

Statement of scientific merit

*The **Head of School*** is required to sign the following statement:*
This proposal has been considered and is sound with regard to its merit and methodology.
The Head of School's (or Head of Discipline's) signature on the application form indicates that he/she has read the application and confirms that it is sound with regard to (i) educational and/or scientific merit and (ii) research design and methodology. If the Head of School/Discipline is one of the investigators this statement must be signed by an appropriate person. This will normally be the Head of School/Discipline in a related area.

This does not preclude the Committee from questioning the research merit or methodology of any proposed project where if feels it has the expertise to do so.

(Name of Head of School) (Signature) (Date)
* In some schools the signature of the Head of Discipline may be more appropriate.
* An investigator on the project may not give the certification of scientific merit.

Conformity with NHMRC guidelines

The *chief investigator* is required to sign the following statement:
I have read and understood the *National statement on ethical conduct in research involving humans 1999*. I accept that I, as chief investigator, am responsible for ensuring that the investigation propose this form is conducted fully within the conditions laid down in the *National Statement* and any ot conditions specified by the University Human Research Ethics Committee.

Dr Kelvin Michael

(Name of chief investigator) (Signature) (Date)

Signatures of other investigators
The other investigators should sign to acknowledge their involvement in the project and to accept the role of the chief investigator.

(Name)	(Signature)	(Date)
Mr David Pointing		
Dr Julia Jabour		

Appendix 6

Information sheet for interview subjects for the project:
"*Interviews to identify current attitudes towards hydrogen energy use in Antarctica and other regions of Australia*"
(3 pages)

INSTITUTE OF ANTARCTIC & SOUTHERN OCEAN STUDIES

Hydrogen Energy Systems in Antarctica
Institute of Antarctic & Southern Ocean Studies
University of Tasmania
Locked Bag 77 Hobart
Tasmania Australia 7001
www.iasos.utas.edu.au/h2esa

10 March 2004

Human Research Project Information Sheet

Project Title: **Interviews to identify current attitudes towards hydrogen energy use in Antarctica and other regions of Australia**

Chief Investigator: Dr Kelvin Michael, Senior Lecturer, IASOS, University of Tasmania
Researcher: Mr David Pointing, PhD research student, IASOS, University of Tasmania

Purpose of the study

To determine the current attitudes of the Australian Antarctic research and support community towards hydrogen energy technologies and the potential for their use within the Australian Antarctic program, via personal interviews of key personnel.

The outcomes from the study will be applied in developing strategies and identifying activities that will assist in the implementation of sustainable energy systems into Australia's scientific research and support activities in Antarctica. The study will also seek to capture the knowledge and experience of other efforts around the world to implement hydrogen energy technologies, which will provide a broader perspective of the current drivers for and barriers to the use of hydrogen energy technologies in society – particularly their use in remote areas.

The study is being undertaken as part of David Pointing's PhD research degree, in which he is investigating the technical and non-technical issues related to hydrogen energy use in Antarctica. This study will contribute to the non-technical assessment.

Participant Benefit

Why should you be involved in this study? Hydrogen energy technologies, when coupled with renewable energy resources, have to potential to significantly improve the environmental, economic and operational performance of energy supply systems over that of the fossil fuel-based facilities currently used by society – including to support Antarctic research programs. Your participation in this study will contribute valuable knowledge towards identifying what actions must be taken to enable the safe, effective and efficient implementation of sustainable energy systems within Australia's Antarctic research program, and will assist in the broader implementation of sustainable energy systems around the world when the knowledge generated from this study is shared with other researchers and energy system implementers.

Results of investigation

The results of the study will be published in Pointing's PhD thesis, due for completion in 2005, and in other publications where appropriate. Participants will be informed of the outcomes of the study at its conclusion. It is not anticipated that significant findings during the study will require the participants to be informed prior to the study conclusion.

Additional information and progress reports on the study can be sourced via the Hydrogen Energy System in Antarctica (H2ESA) Research Program web site, or directly from David Pointing (contact details following).
H2ESA Web site: www.iasos.utas.edu.au/h2esa

Study procedures

This study will include personal interviews with approximately 40 different candidates, grouped within the categories of:

1. implementers of hydrogen energy technologies (implementers),
2. the potential users of such technologies in Antarctica (implementation targets),
3. parties who influence the selection of energy supply systems for operations in Antarctica or other regions (implementation influencers).

The interview candidates, such as yourself, were selected prior to the commencement of the study with your selection based on a desire to capture the views of specific positions/roles within the Australian Antarctic community, or to capture the knowledge of specific parties involved in other hydrogen energy implementation projects around the world. Additional interview candidates may be added to the survey if the need or opportunity arises.

David Pointing will conduct the interviews with the candidates on a 1-1 basis, at a mutually agreeable time and location. The interviews are anticipated to run for approximately half an hour (30 mins), involving verbal answers to approximately 10 interview questions. The interview questions will focus on aspects of your knowledge and perception of hydrogen energy technologies and their use in Australia's Antarctic program or other applications. You will not be informed of the specific questions prior to the interview.

With your permission, interviews will be recorded on audiotape, with a transcript of the session provided after the interview and before the material is used in the study. You will be requested to confirm your approval of the recording and transcript process, and approve the transcript prior to use in the study.

At the conclusion of the interview/transcript approval process, you will be requested to specify how you wish your responses to be used in the study. Potential options include:

1. your responses are compiled into a general list of perceptions and responses, without any specific reference to you as an individual (or your position).
2. you permit direct quotes of your responses where required, and option [1] above.
   For the purposes of the study, [2] is the preferred option for the use of all candidates' responses, however, the right to specify the level of use remains with each candidate Candidates who approve option [2] will be informed of each specific publication that incorporates their response and they retain the right of refusal for each use.

In situations where face-to-face interviews are not possible, the interview questions will be submitted via telephone or via email. In these circumstances, you will retain all the rights you would have if interviewed in person.

Possible risks or discomforts

This study is perceived to have negligible risk that may affect your willingness to participate – the questions asked will be in no way intrusive, and your participation is strictly voluntary. You have the right to withdraw at any time, or to not answer specific questions, and you retain the right to confirm your interview responses prior to their use in the study. You also retain the right to specify how your responses may be used in the study.

Confidentiality

The level of confidentiality required in this study will be influenced by the individual responses of the candidates. All interview material will be retained at IASOS within locked digital or physical storage systems for a 5-year period, after which it will be appropriately destroyed. If you wish your identity to remain confidential, appropriate measures will be taken to separate your details and your responses. Please note that for some specific positions and roles, it is important for the purpose of the study to identify that the role (and hence the individual) has participated. In such circumstances, a level of confidentiality may be applied by you (the candidate) in specifying your desired level of use for your responses. Please feel free to discuss the issue of confidentiality further if you have specific concerns.

Freedom to refuse or withdraw

Your participation in this study is entirely voluntary. If you do decide to participate, you are welcome to withdraw at any time without prejudice, and withdraw any information or data you have supplied.

Statement regarding approval

This project has received ethical approval from the Southern Tasmania Social Sciences Human Research Ethics Committee, who you may contact if you have any concerns of an ethical nature or complaints about the manner in which the project is conducted.

Chair:	A/Professor Gino DalPont	(6226 2078)
Executive Officer:	Amanda McAully	(6226 2763)

If you are a university student and have personal concerns related to the study, you may choose to discuss these concerns confidentially with a University Student Counsellor.

Information sheet and consent forms

Candidates in the study will be provided with copies of the information sheet and statement of informed consent to keep.

Contact persons

If you have further questions about the study, please contact David Pointing (the researcher) or Dr Kelvin Michael (Chief Investigator, David's PhD supervisor).

Dr Kelvin Michael
Senior Lecturer, PhD Supervisor

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Mr David Pointing
Research Engineer & PhD Student

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Dr Kelvin Michael

Mr David Pointing

Appendix 7

Interview questions for the project:
"*Interviews to identify current attitudes towards hydrogen energy use in Antarctica and other regions of Australia*"
(3 pages)

IASOS
INSTITUTE OF ANTARCTIC & SOUTHERN OCEAN STUDIES

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Human Research Project – Interview Questions

"Hydrogen Energy *Implementers*"

Project Title: **Interviews to identify current attitudes towards hydrogen energy use in Antarctica and other regions of Australia**

Questions:

1. What is your interpretation of the term "hydrogen energy", and consequently what sort of technology are you trying to implement?
2. What are the objectives of your efforts for implementation?
3. What is your reason for doing this? (driving forces)
4. Who do you see are the target users?
5. What barriers do you encounter to hydrogen energy implementation and use in the short-term?
6. What strategies do you employ to overcome those barriers?
7. Do you have a view of the long-term barriers that you will face in the future?
8. Do you have a long-term strategy for implementation? Can you briefly describe that strategy?
9. Does your strategy consider the issues surrounding the implementation of hydrogen energy that are both technical and non-technical in nature?
10. Do you think some of the barriers you face today, in the present global climate of hydrogen understanding, climate change etc, will not be present in the future for the next generation of implementers; and are some barriers more persistent? (ie. Are some of the barriers now faced only an artifact of the very limited number of successful implementations?).
11. What are your thoughts on the use of hydrogen energy technologies in remote, harsh and sensitive regions like Antarctica?

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Human Research Project – Interview Questions

"Hydrogen Energy *Implementation Targets*"

Project Title: **Interviews to identify current attitudes towards hydrogen energy use in Antarctica and other regions of Australia**

Questions:

1. How do you use 'energy' in your current occupation?
2. What sort of energy generation systems do you currently use to meet your energy requirements?
3. Do you find that conventional energy technologies (eg. Batteries, petrol and diesel generators etc) are capable of meeting all of the operational/performance demands of the activities that you undertake? If not, in what ways do they fall short?
4. What other problems or failings do you have with these conventional energy technologies, particularly issues not related to their ability to deliver power? eg, environmental impacts, logistical burden of having fuel delivered, limited performance of renewable energy technologies, failure of batteries in cold temperatures etc.
5. What is your understanding of using hydrogen as a means of storing and supplying energy? What are the core technologies?
6. Can you see any roles for hydrogen energy technologies in your operations, and <u>how do you feel</u> about using such systems (feasible)?
7. What advantages do you think H2 technologies might offer over conventional systems?
8. What disadvantages?
9. What do you think the major barriers are to increasing the use of sustainable energy systems in your field of activity, particularly thosc that use hydrogen energy technologies?
10. What do think the 'drivers' are to implement new energy technologies like hydrogen?
11. What do you think should be done to increase the implementation of new energy technologies such as those that use hydrogen as an energy carrier?

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Human Research Project – Interview Questions

"Hydrogen Energy *Implementation Influencers*"

Project Title: **Interviews to identify current attitudes towards hydrogen energy use in Antarctica and other regions of Australia**

Questions:

1. What are the objectives and core values of your organisation?
2. What is your personal role in influencing the selection and implementation of energy supply systems in your organisation?
3. What activities does your organisation currently do that use energy?
4. What energy systems are used to meet the energy requirements?
5. What are the methods, values and policies that are used to select the energy generation systems that are used by your organisation?
6. Do the technologies used meet the practical energy needs of your operations, and do they compliment your core organizational values?
7. What is your understanding of using hydrogen as a means of storing and supplying energy? What are the associated technologies etc?
8. What advantages do you think H2 technologies might offer over conventional systems?
9. What disadvantages?
10. Can you see any roles for hydrogen energy technologies in your operations, would they fit your organisational values, and <u>how do you feel</u> about supporting the evaluation and implementation of such systems?
11. How would hydrogen energy technologies fit with the current methods and policies used to select energy supply systems?
12. What do you think the major barriers are to increasing the use of hydrogen energy technologies in your organisation?
13. What are the drivers to implement technologies like hydrogen?
14. What do you think should be done to increase the implementation of sustainable energy systems and the use of hydrogen technologies?

Appendix 8. Details of community engagement activities

This appendix provides additional information about the community engagement activities undertaken during the research. Issues addressed in further detail include:

1. The list of candidates that were approached for participation in the formal and informal interviews undertaken as a component of the social sciences element of the research, as defined in the application for ethics approval.
2. Workshops delivered by the author
3. Seminars and briefings delivered by the author
4. Research collaboration visits with partner institutions
5. Participation in public events as an expert speaker
6. Conferences attended and papers presented

Formal interview candidates

Organisation	*Position*	*Individual*	*Category*
Australian Antarctic Division (AAD)	Director	Dr Tony Press	Influencer
AAD	Chief Scientist	Dr Michael Stoddard	User/influencer
AAD	Deputy Director	Virginia Mudie	Influencer
AAD	Chief Engineer	Chris Paterson	Implementer
AAD	Innovation & Development Engineer	Peter Magill	Implementer
AAD	Field Training Officers	Don Hudspeth	User
Tasmanian Government	Economic Development Minister	Hon. Lara Giddings	Influencer
Australian Institute of Energy, Hydrogen Division	Secretary	Lui Bonadio	Implementer
Norwegian Polar Institute (NPI)		Birgit Njaastad	Influencer
NPI		Roy Bruun	Implementer
NPI		John Gulder	User/Implementer
Swedish Polar Research Secretariat		Magnus Aulder	Implementer /Influencer
Swedish Polar Research Secretariat		Sven	User
Swedish Polar Research Secretariat		Johan Siddemark	Implementer
University of Technology Sydney		Dr Joe Zhu	Implementer
Norske Hydro		Marit Elizabeth	Implementer
Perth Fuel Cell Bus Trial	Research student	Lisa Garrity	Implementer

Informal interview candidates

Organisation	*Position*	*Individual*	*Category*
AAD	Chief Engineer	Chris Paterson	Implementer /User
AAD		Peter Magill	Implementer /User
AAD		Tom Maggs	Influencer
AAD	Station leader	Marilyn Boydell	User
AAD		Kym Newbury	Implementer /User
IASOS	Researcher, lecturer	Dr Julia-Jabour Green	Influencer
Antarctic Wildlife Research Unit, University of Tasmania (AWRU)	Senior Researcher	Dr Mark Hindel	User
Antarctic Tasmania Office, Tasmanian government Economic Development Department	Director (acting)	Ben Galbraith	Influencer
Council of Managers of National Antarctic Programs (COMNAP)	Executive Director	Dr Antoine Guichard	Influencer
Australian Government, Department of Environment & Heritage, AGO		Joe Wyder	Influencer
Australian Greenhouse Office		Chris Baker	Influencer/ Implementer
International Energy Agency (IEA)	Annex 18 Sub-Program Leader, Hydrogen Implementation	Dr Oystein Ulleberg	Implementer
Berlin Technical University – H2 and Fuel Cell Research Unit	Senior Researcher	Dr Kerry-Anne Adamson	Implementer
Icelandic New Energy, Iceland	Director	Dr Thorsteinn Sigfusson	Implementer
Perth Fuel Cell Bus Trial	Research student	Lisa Garrity	Implementer
		Simon Whitehouse	Implementer /influencer
Australian Institute of Energy, Hydrogen Division	Secretary	Lui Bonadio	Implementer
Australian Institute of	Chair	Dr Andrew Dicks	Implementer

Energy, Hydrogen Division			
CSIRO & National H2 Centre	Senior Scientist	Dr Sukhvinder Badhwal	Implementer
CSIRO & National H2 Centre	Senior Scientist	Dr David Rand	Influencer
University of Tasmania, School of Engineering	Program Leader	Ass Prof Vishy Karri	Implementer
Hydro Tasmania	Manager	John Titchen	Implementer
Hydro Tasmania	Renewable Energy Project Manager	Rob Grant	Implementer
Tasmanian Hydrogen Stakeholders Network	Secretary	Josh Bradshaw	Implementer /influencer
U.K. Antarctic program	Operations representative	David Blake	Implementer
UTAS	PhD candidate, EwB Chair	Todd Houstein	Implementer
Australian Government, Bureau of Meteorology	Director	Dr Geoff Love	Influencer
Australian Government, Bureau of Meteorology		Dr Sue Barrell	Implementer /user
Imperial College London		Dr David Hart	Implementer /influencer
UNEP Risoe Centre for Energy Climate & Sustainable Development		Gordon Mackenzie	Implementer /influencer

Workshops presented or co-presented by the author:

1. 2005: September, Australian Government, Bureau of Meteorology, Melbourne
2. 2005,March, Australian Antarctic Division, Operations Branch, Hobart
3. 2004: September 2004, 2-day HydroGEMS workshop in Perth, W.A., Australia (co-hosted with Ulleberg from IFE)
4. October 2004, Innovation and technology in Antarctic science (engineers perspective for the researchers at the CRC for Antarctic Climate & Ecosystems)
5. 2003: HydroGEMS workshop in Oslo, Norway
6. 2003, July: Hydrogen energy in Antarctic biological sciences
7. 2003, July: visit by CSIRO delegation to discussion formation of National Hydrogen group as outcome of National H2 study.
8. May 2003, Australian Innovation Festival public seminar and expert panel discussion (organiser and speaker)
9. March 2003, Sustainable Transport Week
10. March 2003, "Hydrogen in Tasmania" public seminar for national science week

Seminars and briefings delivered by the author:

1. Australian Greenhouse Office, May 2003
2. Australian Antarctic Division, September 2003
3. Tasmanian Polar Network, March 2004,
4. Tas Govt, Office of Energy Planning, July 2003
5. Australian Government, Bureau of Meteorology, September 2005
6. CSIRO Manufacturing, Industry and Technology, June 2003
7. Swedish Polar Research Secretariat, June 2004, June 2005
8. Norwegian Polar Institute, June 2004, June 2005
9. British Antarctic Survey, July 2002
10. Bellona Foundation (Norway), July 2002
11. Technical University of Berlin, July 2002
12. Australian Fleet Managers Australia Hobart branch, May 2004

Participation in Public events as an expert speaker:

1. National Science Week, 2003, 2004
2. Australian Innovation Festival, 2003
3. Antarctic Mid-winter festival, 2003, 2004

Research collaborations with partner institutions:

1. IFE, Norway

5 visits, totally 18 weeks

2. UTS, Australia

6 visits, totally 5 weeks

3. UNEP Risoe Centre for Energy, Climate and Sustainable Development, Denmark

1 visit, 8 weeks

Conference participation and papers

Council of Managers of National Antarctic Programs (COMNAP) bi-annual meeting

July 2006, Hobart, TAS, Australia

Poster: [1] *Accessing sustainable energy solutions in Antarctica – recommendations for COMNAP*

1st Engineers Without Borders (EwB) Australia conference

29 Nov – 1 Dec 2005, Melbourne, VIC, Australia

***Australian* Co-operative Research Centre Association (CRCA) annual conference (invited speaker)**

18-20 May 2005, Melbourne, VIC, Australia

Key note presentation: [1] *Sustainable energy solutions for Antarctic science*

International Workshop on Hydrogen Technologies for a Sustainable Future (invited participant)

20-23 March 2005, Melbourne, VIC, Australia

Hydrogen and Fuel Cell Futures (H2 in Transport) conference

12-15 September 2004, Perth, W.A., Australia

Paper: [1] *Hydrogen Energy in Antarctica – Applications & Strategies for Implementation*

19th World Energy Congress –Youth Symposium (invited speaker)
5-9 September 2004, Sydney, NSW, Australia
Paper: *Selecting and Implementing appropriate energy technologies: a case study from Antarctica.*

1st Antarctic Climate & Ecosystems Cooperative Research Centre (ACE) Annual Symposium
30-31 August 2004, Hobart, TAS, Australia

15th World Hydrogen Energy Conference
27 June – 2 July 2004, Yokohama, Japan
Paper: [1] *Implementing Hydrogen Energy Systems in Antarctica and other remote, harsh and sensitive environments;* Poster and paper: [2] *Using Hydrogen to Support Science in Antarctica*

1st Canadian-Norwegian Hydrogen energy technology collaboration workshop
May 2004, Oslo, Norway

Australian Fleet Managers Association (AFMA) annual conference
15 & 18th March 2004, Sydney & Melbourne, Australia (invited speaker)
Paper: *Hydrogen – Fuelling the fleets of the future*

Planning Institute of Australia annual conference (invited speaker)
February 2004, Hobart, TAS, Australia; Paper: [1] *Hydrogen – Fuelling the future of Tasmania*

Australian Institute of Energy – Hydrogen Division: Introduction to Hydrogen seminar
3 December 2003, Melbourne, VIC, Australia (invited speaker)
Paper: *Implementing renewable hydrogen systems in Antarctica*

41st ANZSES Annual Conference "Destination Renewables" (invited speaker)
26-29 November 2003, Melbourne, VIC, Australia
Paper: [1] *Developing an Implementation Strategy for the Antarctic Hydrogen Energy Economy*

1st Alternative Fuels Conference, Tasmanian Transport Association (invited speaker)
7August 2003, Hobart, TAS, Australia; Paper: [1] *Hydrogen as an alternative fuel*

Australian Wind Energy Association (AusWEA) 5th Annual Conference (invited speaker)
24-25 June 2003, Sydney, NSW, Australia; Paper: [1] *The windy future of hydrogen in Antarctica*

Commonwealth Government "National Hydrogen Study" Conference (invited participant)
19-21 May 2003, Broome, WA, Australia; Poster papers: [1] *Hydrogen Energy in Antarctica;* and, [2] *Education and Outreach with Hydrogen Energy demonstration programs*

1st Workshop for the DITR Australian "National Hydrogen Study" (invited participant)
27-28 March 2003, Melbourne, VIC, Australia

Australian and New Zealand Solar Energy Society (ANZSES) "Solar Harvest"
27-30 November 2003, Newcastle, NSW, Australia; Papers: [1] *Hydrogen Energy - A Vision for Tasmania*; and,
[2] *Hydrogen Energy in Antarctica – Examining the Arguments and Opportunities*

Australian Academy of Technological Science & Engineering (AATSE) (invited participant)
Annual Symposium – "Owning Innovation – from idea to delivery"
November 2003, Sydney, Australia (selected to attend as a Young Symposium Fellow).

Institution of Engineers Australia conference "Engineering A Sustainable Future"
2-3 September 2003, Hobart, Tasmania, Australia

14th World Hydrogen Energy Conference – "the Hydrogen Planet"
9 –13 June 2003, Montreal, Quebec, Canada
Poster: [1] *Hydrogen in Antarctica – is Antarctica an early market adopter*

Australian and New Zealand Solar Energy Society (ANZSES) "Solar Harvest"
27-30 November 2002, Newcastle, NSW, Australia
Papers: *Hydrogen Energy - A Vision for Tasmania*; and,
Hydrogen Energy in Antarctica – Examining the Arguments and Opportunities

Academy of Technological Science & Engineering Annual Symposium – "Owning Innovation – from idea to delivery"
November 2002, Sydney, Australia (selected to attend as a Young Symposium Fellow).

Institution of Engineers Australia "Engineering A Sustainable Future"
2-3 September 2002, Hobart, Tasmania, Australia
Papers: *A Sustainable Future for Engineering?;* and,
Is Hydrogen Ready for Antarctica? What are the business opportunities for Tasmania?

14th World Hydrogen Energy Conference – "the Hydrogen Planet"
9 –13 June 2002, Montreal, Quebec, Canada
Poster: *Hydrogen in Antarctica – is Antarctica an early market adopter*

H2002 – 1st Mini-seminar & Workshop on Hydrogen Energy Systems Modelling
30 April – 1 May 2002, Murdoch University, W.A., Australia

Relevant conferences completed before the PhD was commenced:

International Solar Energy Society (ISES) – "Solar World Congress"
25 Nov – 2 Dec 2001, Adelaide, S.A., Australia
Poster: *Hydrogen Energy in Antarctica* (winner of best "young researcher" poster prize).

Australian Academy of Technological Science & Engineering Annual Symposium – "Looking South – Managing Technology, Opportunity & the Global Environment"
20 – 21 Nov 2001, Hobart, TAS, Australia (selected to attend as Young Symposium Fellow).

University of Tasmania – "Antarctica: Past, Present & Future Conference"
22 June 2001, University of Tasmania, Hobart, TAS, Australia

ISCORD Symposium on Cold Region Development
31 Jan – 6 Feb 2002, Hobart, TAS, Australia

International collaborative project proposal:

Sustainable energy systems for polar communities via renewable hydrogen energy technologies

David Pointing
University of Tasmania, Institute of Antarctic & Southern Ocean Studies

To establish an international collaborative project to develop, implement and evaluate sustainable energy systems for Antarctic, Arctic and remote communities - based on the use of renewable energy technologies and hydrogen as an energy carrier.

Key elements of the proposal:

- A framework to capture and effectively share the results of existing efforts to develop sustainable energy systems for polar and remote communities.
- A critical mass of international and multi-disciplined researchers, with strong links to technology developers and user communities, to identify and address the technical and non-technical challenges associated with developing and implementing sustainable energy solutions for polar and remote communities.
- Undertake specific R&D activities that take advantage of the links between Antarctic and Arctic operations to fast-track the development and implementation of sustainable energy systems for polar and remote communities.

Proposal Details:

The project will establish an international collaboration of researchers and user communities to develop, evaluate and implement sustainable energy systems for the betterment of communities in polar and remote environments. This will involve researchers in the fields of energy systems, polar operations and engineering, community engagement and the social sciences.

The project will focus on the development opportunities that emerge when the research and development of energy systems for Arctic and Antarctic communities is undertaken in an integrated manner, and the broader roles that such communities can play in serving as economically or environmentally viable early market adopters of emerging sustainable technologies – particularly renewable and hydrogen energy technologies.

The project will initially provide a framework to link the existing and relatively independent efforts of researchers and/or communities from around the globe to implement sustainable energy technologies in Antarctic, Arctic and remote communities. This framework will enhance the sharing of knowledge and experiences between the currently isolated activities, reduce the duplication of effort, and identify key areas of research and development that are not being addressed by the current activities. The strengthened connections between user communities and research groups that will result from the framework will also assist in better directing research efforts towards genuine community needs.

The project will subsequently become a focus for a range of international multi-disciplined research and development activities which will aim to address the many technical and non-technical issues associated with the development, implementation and on-going use of the innovative technologies and processes related to providing sustainable energy solutions for communities.

Short-term outcomes and benefits:

- The project will establish a critical mass of parties and expertise focusing on the development and implementation of practical solutions to provide sustainable energy systems for remote and polar communities. This will provide a strong impetus to develop viable systems and products (tangible solutions) for use in real-life communities. This will also enhance opportunities to engage industries in developing market-ready products and solutions by providing a coherent demand for products to service an identified market-base.
- The project presents a cost-effective strategy to develop, deploy, evaluate, and potentially commercialize viable sustainable energy solutions for remote communities by targeting applications that have strong drivers to become early-market adopters of innovative energy technologies if products are available (scientific or conventional communities in remote and pristine environments with critical energy security needs).
- The project will result in the growth or development of international collaborations in a variety of research fields, enabling the transfer of skills and technology between partners. The project offers considerable opportunities for the involvement of students and peripheral researchers in the broader objectives of the project.
- The project offers a high potential for commercialisation of technology, products, tools and expertise for the participating organisations due to the strong focus on ultimately developing market-ready solutions.
- The project will enable the uptake of sustainable energy technologies by remote and polar communities and subsequently generate potential areas for industry development to support such markets.
- The project will address recognised problems in the implementation of sustainable energy systems in Antarctic and Arctic operations by developing fertile links between polar communities and the international energy and policy research communities and subsequently developing the solutions required to enable the uptake of appropriate technologies by common communities.

Long-term outcomes:

"Antarctica – the first clean energy continent"
This project can assist the international community in making the pristine Antarctic continent the first 'clean energy continent' on the planet. To assist, the project will establish links between researchers and operations personnel to develop and implement clean energy systems for Antarctic operations, introduce multidiscipline research programs related to the introduction of sustainable technologies, establish a cost-effective development program based on applying Arctic research to the Antarctic environment, and provide a tangible link between investments in Antarctic energy system research to the broader community to strengthen arguments for continued investment in Antarctic-focused systems by governments or technology developers.

"Competitive, clean and secure energy supplies for polar and remote communities"
The project will also enhance the transfer of outcomes and technologies developed via government investment in "early-adopter" Antarctic and Arctic energy systems to the less competitive polar and remote community energy markets, assisting in the long-term development of sustainable energy solutions for remote communities in developing and developed nations around the world.